International workshop on Growth, characterization and exploitation of epitaxial compound semiconductors on novel index surfaces (NIS'96)

Lyon (France) 7-9 Oct 1996

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Organising Committee :

- **Prof G. Guillot (Chairman) INSA - Lyon**
- **Dr M. Henini University of Nottingham**
- **Prof. E. Munoz University Madrid**
- **Dr L. Pavesi University of Trento**

PROGRAMME

Monday morning :

8.30	Registration and opening remarks
9.00	DL Smith Piezoelectric effects in strained layer heterostructures grown on novel index surfaces.
9.50	L. Pavesi Photoluminescence investigations of GaAs on non (100) surfaces.
10.40	Coffee break

11.10	E. Mao, S.A Dickley, and A. Majerfeld, B.W Kim High quality GaAs/AlGaAs quantum wells grown on (111)A substrates by metalorganic vapor phase epitaxy.
11.30	P. Ballet, P. Disseix, A. Vasson, A.M Vasson and R.Grey Optical investigation of piezoelectric field effects on excitonic properties in (111)-B-Grown (In,Ga)As/GaAs quantum wells.
11.50	E.Sano, Y. Hirayama, and Y. Horikoshi Selenium doping in high-index GaAs epilayers grown by molecular beam epitaxy.
12.10	P.O Vaccaro, K. Fujita and T. Watanabe Piezoelectricity and carrier dynamics in $In_{0.2}Ga_{0.8}As$/GaAs single quantum wells grown on (n11)A-oriented GaAs (n=1,2,3).
12.30	J.F Valtueña, I. Izpura, J.L Sanchez-Rojas, E. Muñoz, E.A Khoo, JPR David, R. grey, J. Woodhead, G.J. Rees. Memory effects on piezoelectric InGaAs/GaAs MQW PIN diodes.

Monday afternoon :

13.00	Lunch
14.30	A. Fasolino Electronic states in QWs grown on high index surfaces.
15.20	JL Sanchez-Rojas, A.Sacedón, J.F Valtueña, I.Izpura, E. Calleja, E. Muñoz. Charge accumulation effects in InGaAs/GaAs MQWs (111) oriented piezoelectric MQW.
16.10	Coffee break
16.40	A. Sanz-Hervás, C. Villar, A. Sacedon, J.L Sanchez-Rojas, E.J Abril, M. Garrido, M. Aguilar, E. Calleja, M. Lopez, E. Muñoz Application of high-resolution X-ray diffractometry to the structural study of epitaxial multilayers on novel index surfaces.
17.00	H.G Colson, P. Kidd and D.J Dunstan Critical thickness and relaxation of (111) oriented strained epitaxial layers.
17.20	M.Y Simmons, A.R Hamilton, S.J Stevens, D.A Ritchie, M.Pepper. A study of the mobility anisotropy in front and back-gated (311)A hole gas heterojunctions.
17.40	Poster session
19.30	Dinner
21-22h30	Poster session in the evening

Tuesday morning :

8.30	H. Heinecke Facet formation and characteristics of III-V structures grown on patterned surfaces.
9.20	L. Pfeiffer, A. Yacoby, H.L Stormer, K.L Baldwin, J. Hasen Transport and optics in quantum wires fabricated by MBE overgrowth on the (110) cleaved edge.
10.10	Coffee break
10.40	C. Priester and S.J Sferco Strain distribution in quantum wires fabricated by MBE overgrowth on the (110) cleaved edge of a strained superlattice.
11.00	H.Yamaguchi, J.G Belk, X.M Zhang, J.L Sudijono, M.R Fahy, TS Jones, BA Joyce. RHEED and STM study of two dimensional growth of InAs on GaAs (111)A surfaces.
11.20	E.S Tok, J.H Neave, M.R Fahy, F.D Allegretti, J.Zhang, T.S Jones, B.A Joyce. As_2 and As_4 incorporation kinetics on the GaAs(110) surface: implications for growth and doping.
11.40	M. Wachter,C. Menke, and H. Heinecke. Anisotropic surface diffusion at crystal facet transitions during localized Ga-In-As-P growth MOMBE.
12.00	T. Marschner, F.D Tichelaar, M.R Leys, R.T Rongen, H. Vonk, J.H Wolter Effects of Tensile strain and surface steps on epitaxial layer morphology of CBE grown GaInAs/InP multiple quantum well structures.
12.20	A. Ponchet, A.Rocher, A. Ougazzaden and A. Mircea InAsP/GaInP strained multilayers grown by MOVPE on (001), (113)B and (110) InP substrates : the role of the surface characteristics.
12.40	F. Peiro, A. Cornet, J.R Morante and G.Georgakilas. Self organization of quantum wire-like on $In_xGa_{1-x}As$ single quantum wells grown on (100) InP vicinal surfaces depending on the substrate misorientation, buffer mismatch and growth temperature.
13.00	Lunch

Tuesday afternoon :

14.30	RN. Nötzel Self-organization of microstructures on high index semiconductor surfaces.
15.20	K. Eberl Direct synthesis of quantum dots for single-electron transistors and laser diodes.
16.10	Coffee break
16.40	H. Hasegawa and H.Fujikara Formation of InP based quantum structures by selective MBE on patterned substrates having high-index facets.
17.30	M. Geiger, F. Adler, U.A Griesinger, H. Schweizer, F. Scholz. GaInAs/InP quantum wires grown by metalorganic vapor phase epitaxy on V-grooved InP substrates.
17.50	A.P Roth, P. Finnie, C. Lacelle, C. Guérini, J. Fraser, M. Buchanan, Y. Feng. Growth by selective area epitaxy on patterned substrates and characterization of GaInAs/InP nanostructures.
18.10	G. Biasiol, F.Reinhardt, A. Gustafsson, E.Kapon. Low pressure OMCVD growth of V-Shaped quantum wires.
18.30	Round table.
20.30	Conference Dinner.

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Wednesday morning :

8.30	N. Ledentsov 3D arrays of self-ordered quantum dots for laser applications : growth and properties.
9.20	JM. Gérard, J.Y Marzin. Intrinsic limitations and potential applications of InAs QBs obtained by self organized MBE growth.
10.10	Coffee break
10.40	M.S Skolnick, D.J Mowbray, M.J Steer, W.R Tribe, J.S Roberts, A.G Cullis, G. Hill, C.R Whitehouse, G.J Rees, G.M Williams. Optical and structural studies of MOVPE grown GaAs-AlGaAs v-groove Quantum Wires.

11.00	L. Brusaferri, E. Grilli, M. Guzzi, S. Sanguinetti, MD Upward, M. Henini, P. Moriarty, PH Beton. Structural and optical characterization of self organized InAs-GaAs quantum dots grown on high index surfaces.
11.20	J.Groenen, R. Carles, E.Chimenti, G. Attolini, C. Pelosi, PP Lottici. Spatially resolved optical spectroscopy of GaAs islands on InAs (111).
11.40	N.T Pelekanos, Guido Mula, N. Magnea, J.J Pautrat. Novel piezoelectric-barrier heterostructure for all-optical light modulation.
12.00	C. Guerret-Piécourt, B. Garcia Carretero, C. Fontaine. Growth of (111)B growth multilayers for optoelectronic devices.
12.20	J. Greenberg, L. F. Eastman. 1.3µm lasers on GaAs(111)B employing ordered $(InAs)_1(GaAs)_1$ quantum wells for high frequency response applications.
12.40	Lunch

Wednesday afternoon :

14.00	GJ. Rees Strained layer piezoelectric semiconductor devices.
14.50	J. Nagle, X. Marcadet (111) - oriented substrates for optoelectronic device applications.
15.40	End of the workshop.

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POSTER SESSION

Poster 1	J. Platen, C. Setzer, P. Geng, W. Ranke, K. Jacobi LEED and photoemission study of MBE-prepared GaAs(112),(113), and (114) surfaces.
Poster 2	V. Drouot, S.J Brown, D.A Ritchie, T.M Burke. Growth studies of self-organized InAs dots on (100), (311) and patterned GaAs substrates.
Poster 3	J.M Schneider, J. Ziegler, H. Heinecke. Incorporation behaviour of carbon and silicon on (100) and (111) surfaces during growth of GaAs and $Ga_{0.47}In_{0.53}As/InP$ by molecular beam epitaxy.
Poster 4	J. Gerster, J.M Schneider, C. Ehret, W. Limmer, R. Sauer, H. Heinecke. Spatially resolved Raman investigation of Si-doped GaAs layers on patterned GaAs(100) substrates grown by MBE.
Poster 5	S.D Perrin, D.G Moodie. Growth of strained GaInAsP materials on (111)B oriented InP substrates by atmospheric pressure MOVPE.
Poster 6	C.S Son, S. Il Kim, E.K. Kim, S.K.Min, I.H.Choi. Dependence of electrical properties on the crystallographic orientation of CBr_4^- doped GaAs epilayers grown on GaAs substrates by metalorganic chemical vapor deposition.
Poster 7	N. Galbiati, E. Grilli, M. Guzzi, M. Henini, L. Pavesi. Is the Be incorporation the same in (311)A and (100)AlGaAs?
Poster 8	B. Zhang, T. Yasuda, Y. Segawa. Optical study of ZnSe grown on GaAs (110) surface.
Poster 9	A. Vilà, A. Cornet, J.R Morante, A. Georgakilas, G. Halkias. Structural characterization of InGaAs/InAlAs quantum wells grown on (111)-InP substrates.
Poster 10	D. Lacombe, A. Ponchet, J.M Gérard, O. Cabrol. Structural comparison of arrays of InAs quantum boxes grown respectively on a GaAs substrate and on a GaAs-on-Si substrate.
Poster 11	M.B Derbali, J. Medded, H. Maaref, P. Abraham. Optical characterization of high mismatched InP/GaAs(111) epitaxial layers.

Poster 12	M. Fahy, P. Vaccaro, K. Fujia, M. Takahash, B.A Joyce, T. Watanabe. The Growth of InGaAs quantum well on GaAs(111)A,(211)A and (311)A substrates
Poster 13	N. Bécourt, A. Georgakilas, G. Halkias, C. Bru-Chevallier, T. Benyattou, G. Guillot. Strain induced piezoelectric field in $In_xGa_{(1-x)}As/In_{0.52}Al_{0.48}As$ quantum wells grown on (111)N InP substrate.
Poster 14	C. Bru-Chevallier, G. Archinard, G. Guillot, A. Chin. Piezoelectric constant determination from photoreflectance measurements in strained InGaAs/AlGaAs layers grown on polar substrates.
Poster 15	K. Fujita, H. Ohnishi, P.O Vaccaro, T. Watanabe. MBE growth of AlGaAs/GaAs double-heterostructure LEDs on GaAs(111)A and (211)A substrates using all-silicon doping.
Poster 16	H. Ohnishi, K. Fujita, T. Watanabe. Lateral tunneling transistors fabricated by plane-dependent Si-doping in nonplanar epitaxy on GaAs(311)A and (411)A substrates.
Poster 17	G. Grenet, M. Gendry, Y. Robach, P. Krapf, L. Porte, G. Hollinger. Role of surface energy of (001) and (11n) facets on the 2D to 3D growth mode transition of strained $In_xGa_{1-x}As$ layers on InP(001).
Poster 18	R. Rincón, C. Priester,G. Fierling, X. Letartre, P. Viktorovitch. Piezoelectric effect in micromachined [001] quantum wells : theoretical aspects.
Poster 19	D. Brinkmann, G. Fishman Comparison theory-experiment in T-shaped quantum well wires.
Poster 20	M. Djafari Rouhani, R. Malek, S. Kersulis, V. Mitin. Computer simulation of the growth of heterostructure systems.
Poster 21	A. Tandia, VV Pham. Defects density influence on the Si/SIO_2 interface roughness by atomic scale simulation.

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Piezoelectric Effects in Strained Layer Heterostructures Grown on Novel Index Surfaces

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III-V semiconductors are piezoelectric and therefore electric polarization fields can be generated in strain layer III-V heterostructures. The magnitude and orientation of the strain induced polarization fields depends on the symmetry of the strain which in turn depends on the orientation of the surface on which the heterostructure is grown. For a strain generated polarization field to occur in a zincblend semiconductor, the strain must distort the angles of the cubic unit cell away from 90 degrees. The strains which occurs in the common (100) oriented heterostructures do not distort the 90 degree angles of the cubic unit cell and no electric polarization fields are generated in heterostructures grown on this surface. However, on every other surface orientation, polarization fields are generated in strained layers. For strained layers grown on (111) surfaces, the polarization field is oriented along the surface normal and for strained layers grown on (110) surfaces the polarization fields lie in surface plane. For growth on other surfaces there is both an in plane and a surface normal component. For strained layers with a surface normal component of the polarization field, there is a divergence of polarization; that is, a sheet of polarization charge, at the interfaces of the strained layers. For typical strained layer parameters, the sheets of polarization charge corresponds to of order 10^{12} e/cm^3 and lead to electric field of order 10^5 V/cm. These electric fields lead to large changes in the optical properties of the heterostructure which can be externally modulated to make, for example, electro-optic devices. They can cause charge accumulation which can be used in field effect transistor and resonant tunneling structures. The consequences of strain induced polarization fields on the material and device properties of strained layer heterojunctions will be discussed.

Photoluminescence investigations of GaAs on non (100) surfaces

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The photoluminescence of GaAs grown on non (100) oriented surfaces will be presented and reviewed. A particular care will be paid to show how photoluminescence can help the understanding of the behaviour of the dopants, unwanted impurities and point defects in differently oriented samples.

Low temperature CW and time resolved luminescence data will be presented of (100), (111)A, (111)B, (211)A, (311)A, (311)B, and (110) samples with different doping levels.

High Quality GaAs/AlGaAs Quantum Wells Grown on (111)A Substrates by Metalorganic Vapor Phase Epitaxy

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There is growing interest on (111) Quantum Well (QW) structures both because of the possibility of exploiting the piezoelectric effect and also the enhanced optical properties in comparison with structures grown on (100) oriented substrates. Unlike the growth of GaAs, AlGaAs and their heterostructures on (111)B GaAs substrates, for which there has been considerable investigation during the last few years, the growth and properties of materials and heterostructures on (111)A GaAs substrates have been less reported. Using the Metalorganic Vapor Phase Epitaxy (MOVPE) process it was reported that GaAs and AlGaAs layers can be grown on the (111)A face at temperatures in the range 550-700 °C with good surface morphology [1]. However, to our knowledge, GaAs/AlGaAs QWs grown by MOVPE on the (111)A face have not been achieved. There is a recent report on high quality GaAs/AlGaAs QWs grown on misoriented (111)A substrates by Molecular Beam Epitaxy (MBE) at temperatures of 680-720 °C [2]. In this paper we report the first GaAs/AlGaAs QWs grown on exact and misoriented (111)A substrates by MOVPE at lower temperatures than by MBE and their optical properties, as well as a comparison with MOVPE QWs on (111)B substrates. The QWs were grown on semi-insulating nominally exact (111)A GaAs substrates using an horizontal atmospheric MOVPE machine. The structures were grown at T=600-660 °C and an As/Ga (V/III) ratio of 15-45. The QW structure contains a 750 nm AlGaAs (x=0.2) buffer, a GaAs well, and a 60 nm AlGaAs (x=0.2) cap. Two well thicknesses were investigated: 14 nm and 6 nm. The samples show a specular surface morphology and the defect density decreases with increasing growth temperature, which is attributed to the improving AlGaAs quality. For a sample grown at 660 °C the surface is almost defect free; the average distance between defects is larger than 500 microns. The surface morphology of the exact (111)A samples is better than that of samples simultaneously grown on (100) and 2 deg misoriented (111)A substrates towards the [-2,1,1] direction. For GaAs grown on the (111)B face, good surface morphology could only be obtained at 720 °C.

The optical properties of the QWs were investigated by Photoluminescence (PL) and Photoreflectance (PR). It was found that the PL signal strength increased with growth temperature. A strong band-to-band transition PL signal was observed for the QW sample grown on the exact (111)A face at 660 °C which is twice as strong as that from the QW on a (100) substrate. An excellent theoretical fit of the narrow lineshape PR data indicates that the QWs on exact (111)A substrates have smooth interfaces. Finally, it should be noted that the relatively low growth temperatures required for the (111)A face should allow the growth of InGaAs/AlGaAs QWs at a constant temperature.

[1] M. Umemura et al, J. Appl. Phys. 72, 313 (1992).

[2] A. Chin and K. Lee, Appl. Phys. Lett. 68, 3437 (1996).

OPTICAL INVESTIGATION OF PIEZOELECTRIC FIELD EFFECTS ON EXCITONIC PROPERTIES IN (111)B-GROWN (In, Ga)As/GaAs QUANTUM WELLS.

P. Ballet*, **P. Disseix***, **A. Vasson***, **A-M. Vasson*** and **R. Grey**†

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Strained [111]-oriented InGaAs/GaAs quantum well structures are very attractive for novel non-linear optical and optoelectronic device applications because of the presence of large piezoelectrically induced built-in electric fields.

Excitonic properties of $In_{0.15}Ga_{0.85}As$/GaAs multiple quantum wells, grown by molecular beam epitaxy on (111)B GaAs substrates, are investigated by using thermally-detected optical absorption (TDOA) and electroreflectance (ER). TDOA is a non conventional technique which consists of the detection of the non radiative de-excitation, occuring after the absorption, via the heating of the sample. Two samples containing respectively 7 and 14 wells are studied. The quantum well thickness is 100 Å and the wells are separated by 150 Å GaAs barriers. The whole quantum structure is embedded in the intrinsic region of a p-i-n diode. The substrate is oriented 2 degrees towards $(2\bar{1}\bar{1})$.

The lineshape analysis of the ER spectra for different applied bias voltages is carried out within a multilayer model. A standard damped oscillator represents the optical properties of excitons via the dielectric function changes induced by electric field modulation. The staircase approximation of the transfer-matrix formalism is used to calculate the envelope wave functions of the quasibound states in the presence of internal piezoelectric and p-i-n fields under an external applied voltage. The electric fields in the wells and barriers are determined from the total potential drop across the intrinsic region which depends upon the number of wells. The components of the electric fields in the barrier and in the well differ by the piezoelectric field discontinuity. A variational calculation of the binding excitonic energy and of the oscillator strength is performed within this formalism.

These calculations enable the excitonic transition energies, including the binding energy correction, to be determined in the range of the applied voltages investigated. The fit of the optical transition energies involving the fundamental and several excited levels of electrons and holes leads to an accurate determination of the strength of the piezoelectric field.

The variation of the theoretical oscillator strengths as a function of in-well field is compared with that deduced from the fit to the ER lineshape. In the high polarisation regime, the calculations give oscillator strength values larger than those obtained experimentally. This discrepancy is mainly attributed to a carrier escape phenomenon.

Selenium Doping in High-index GaAs Epilayers Grown by Molecular Beam Epitaxy

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There have recently been a number of reports on GaAs growth on substrate orientations other than (001) because of an increase interest for potential application to low dimensional structures [1]. Silicon is used as the conventional n-type dopant for molecular beam epitaxy (MBE) growth of GaAs(001). However, it behaves as an acceptor on GaAs(N11)A and (110) substrates at low V/III ratios and/or high growth temperatures. Although group VI impurities, such as Se, are expected to be used as stable n-type dopants even for high-index planes, few works have been reported so far [2]. Therefore, we studied Se doping characteristics of high-index GaAs epilayers.

We grew Se-doped GaAs epilayers on GaAs (411) and (711) A and B substrates and (001) substrates. The MBE growth was carried out at 510°C and 580°C by mounting all kinds of substrates on a single molybdenum block. The Se concentration was controlled by the Se-cell temperature. The growth rate of GaAs was adjusted to 1ML/s and we grew 1-μm-thick Se-doped GaAs films on all of the substrates.

Figure 1 shows active carrier concentration as a function of the Se concentration. The Se concentration was estimated from the data of secondary ion mass spectroscopy. It is noteworthy that the depth profiles obtained for the smooth film grown on the (411)A substrate indicate uniform depth distribution of Se without a segregation effect up to the extremely high Se concentration of 7×10^{20} cm^{-3}. The active carrier concentration was measured by the van der Pauw method at room temperature. All of the films grown on high-index substrates showed a stable n-type conduction and the electrical activation efficiency of Se was almost 100% up to Se concentration of 10^{19} cm^{-3}. The saturation of carrier concentration started above 10^{19} cm^{-3} for all indexes. Our results, however, differ from previous results obtained for Si-doped layers grown on GaAs(001) [3,4], that is, carrier concentration increases up to 1.5×10^{20} cm^{-3} Se concentration. The carrier concentration reached at this Se concentration was 2.1×10^{19} cm^{-3} for the film grown on the (411)B substrate (activation rate of 14%).

Furthermore, it is very important that we could obtain extremely flat films with no detectable defects even at the Se concentration of 7×10^{20} cm^{-3} as for the films grown on (411)A and (711)B substrates. Figure 2 shows the microscopic photoluminescence(PL) measurement at room temperature. Figure 2 (a) is for the film grown on (411)A substrate and (b) is for that grown on (001) substrate. The Se concentration is 1.5×10^{20} cm^{-3}. The PL intensity maps are drawn at a wavelength of 7900A in (a) and 7990A in (b). These values correspond to the peak wavelengths of PL spectra and almost agree with our expectation based on the Burstein-Moss shift. The PL intensity of the film grown on (411)A is uniform and slightly stronger than that grown on (001). This measurement indicates that the crystalline quality of (411)A GaAs layers is superior to that of (001) layers even for extremely high Se concentration. Similar results were also obtained for the layers grown on (711)B substrate.

In conclusion, the observed results indicate that the Se doping for high-index epilayer is promising for achieving a good quality n-type GaAs epilayer with extremely high carrier concentration.

[1] R. Nötzel et al., J. Vac. Sci. Technol. **A10** (1992) 617.

[2] H. Ohnishi et al., J. Cryst. Growth **150** (1995) 231.

[3] M. Heiblum et al., J. Appl. Phys. **54** (1983) 6751.

[4] I. Fujimoto et al., Proc. Int. Conf. on the Science and Technology of Defect Control in Semiconductors, Yokohama, 1990, p. 1015.

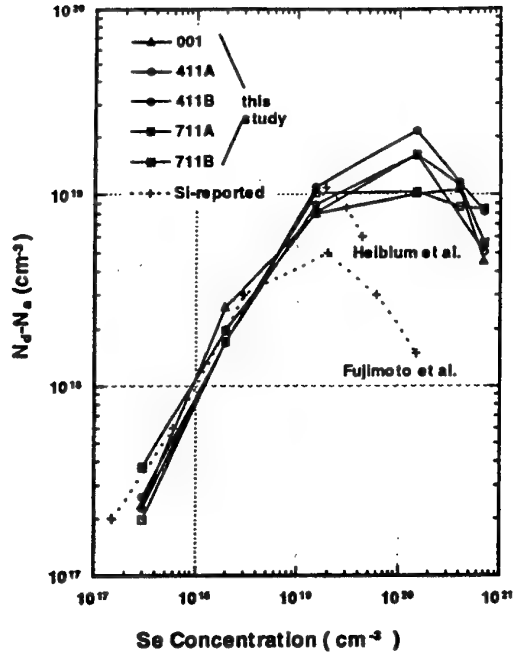

Fig. 1 Active carrier density as a function of Se concentration for the films with several kinds of index grown at 510°C. The reported results for Si-doped (001)GaAs layers are also shown for reference.

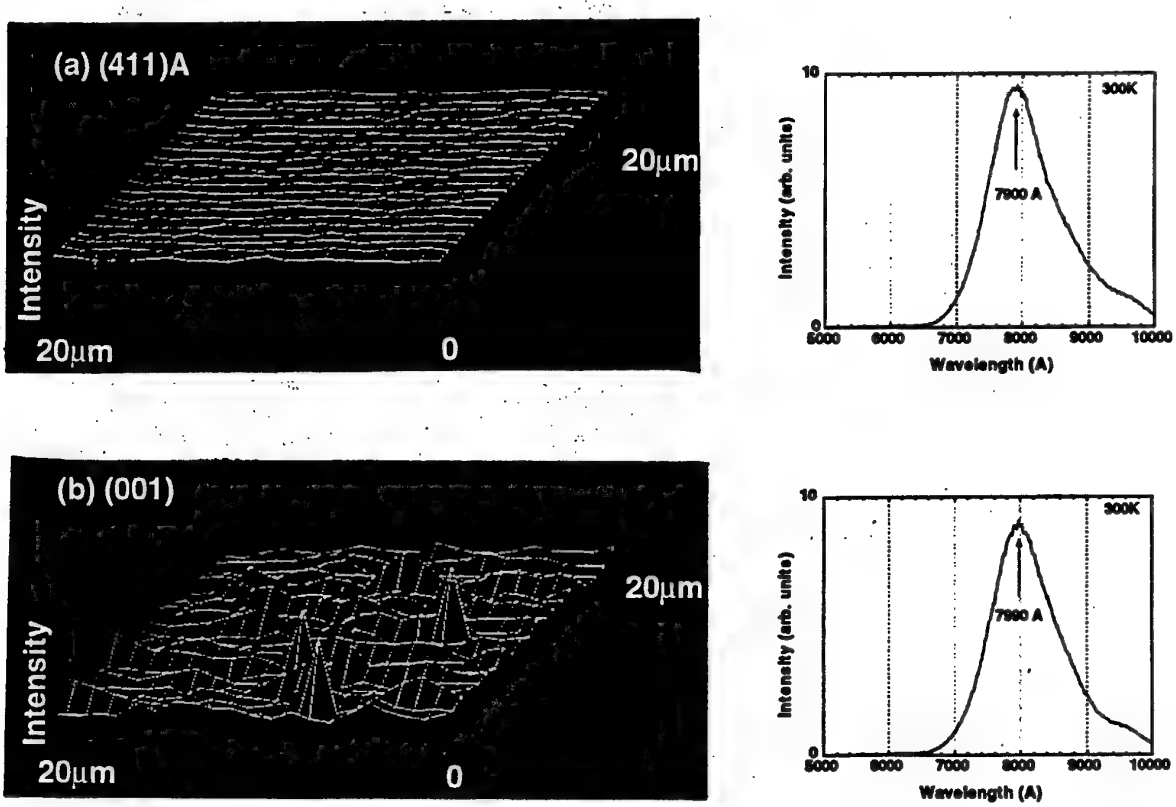

Fig. 2. Microscopic photoluminescence of the films grown on (a) (411)A substrates and (b) (001) substrates. PL intensity spatial distribution and PL spectra.

Piezoelectricity and carrier dynamics in $In_{0.2}Ga_{0.8}As/GaAs$ single quantum wells grown on (n11)A-oriented GaAs (n=1, 2, 3)

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Strained quantum well (QW) structures of InGaAs/GaAs usually have been grown on (100)-oriented substrates. Recently there has been interest in SQWs grown on substrates with other orientations because the piezoelectric effect generates a built-in electric field that produces a large redshift according to the quantum-confined Stark effect (QCSE).[1,2] All but a few of these structures have been grown on (111)B-oriented substrates because it gives the largest built-in electric field. (111)A-oriented substrates give the same built-in electric field but crystal growth is more difficult.[3] Recently, we have grown successfully InGaAs SQWs on GaAs (111)A-oriented substrates and demonstrated the blueshift of the photoluminescence (PL) peaks with applied voltage bias in a *p-i-n* diode structure.[4] The electric field in SQWs grown on gallium terminated (A) substrates has the opposite direction of SQWs grown on arsenic terminated (B) substrates.

Optical nonlinearities are observed in these structures when the electric field is screened by photogenerated carriers. The carrier dynamics of the electric field screening has been studied in multiple QW structures measuring the absorption coefficient dependence on carrier density.[5,6] These experiments show that the electric field screening is mainly due to carriers that escaped from the wells and screen the entire multiple QW structure. The dynamics of the electric field screening inside each quantum well cannot be properly studied in these multiple QW structures.

In this paper, we report temporal variations of the photoluminescence (PL) peak wavelength due to screening of the piezoelectric field by photogenerated carriers in $In_{0.2}Ga_{0.8}As/GaAs$ single quantum wells grown on (n11)A-oriented substrates (n=1, 2, 3) by using time-resolved and wavelength-resolved measurements of the PL intensity decay. The partial screening of the piezoelectric field by photogenerated carriers shifts the PL peak to shorter wavelengths and increases the oscillator strength for optical transitions. The subsequent decrease of the photogenerated carriers by recombination shifts the PL peak back toward longer wavelengths. This redshift produces an initial increase of the PL intensity with time in the long wavelengths, which is explained using a model that fits successfully the experimental results. The model is based on rate equations of photogenerated carriers and a recombination probability which is a function of the screened electric field.

References

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3) P. O. Vaccaro, M. Takahashi, K. Fujita and T. Watanabe, J. Appl. Phys. 76,8037 (1994).
4) P. O. Vaccaro, K. Tominaga, M. Hosoda, K. Fujita and T. Watanabe, Jap. J. Appl. Phys. 34, 1362 (1995).
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6) D. R. Harken, X. R. Huang, D. S. McCallum, A. L. Smirl, J. Sanchez-Rojas, A. Sacedon, E. Calleja, and E. Muñoz, Appl. Phys. Lett. 66,857 (1995).

Memory effects on piezoelectric InGaAs/GaAs MQW PIN diodes.

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Abstract

Charge accumulation effects in piezoelectric MQW InGaAs/GaAs PIN diodes on (111)B GaAs substrates have been studied regarding memory applications. Configurations of Negative Average Electric Field (N AEF) allow storage of a dipole with spatially separated electrons and holes that have low recombination probability and long life times. A light pulse or a forward voltage pulse are able to create the dipole (data writing). This produces a long range screening of the field in the active region and hence a strong blue shift of the absorption band edge (maximum light transmission for reading action). The stored charge can be eliminated by a tailored electrical pulse (data erasing obtaining minimum light transmission).

Capacitance techniques have been proved to be very sensitive to the carrier accumulation in the active region. Capacitance voltage and time resolved capacitance measurements, after single optical or electrical charge pulse at low temperature have been used to determine the stored dipole behavior.

For a given state of charge three different regions with a local maximum are clearly observed in the C-V characteristics (Figure 1). For bias voltages well above the maximum, the capacitance shows a constant voltage shift from the C-V curve taken under dark, from which the screened voltage can be obtained. We associate this behavior to a dipole entirely confined at the band minima of the extreme QW. When bias voltages approach zero AEF (with charge) the capacitance increases due to the spreading of the charge distributions (e- and h+) inside the active region before recombination occurs. Finally, at lower bias voltages, recombination and charge extraction processes are allowed. By reverse biasing the device above zero AEF condition without charge, the stored charge is completely swept out.

Analysis of the capacitance transients has been performed to evaluate the time constant of the discharge process. The results show a non exponential behavior with storage times longer than hours, suggesting very long refresh cycles. Time resolved photocurrent has been used to check read an write capabilities giving on-off ratios up to 20, Figure 2.

The electrical and optical writing properties, electrical and optical read out, easy electrical erase, and the long retention time make this device useful for electrooptical long time refresh memory based devices.

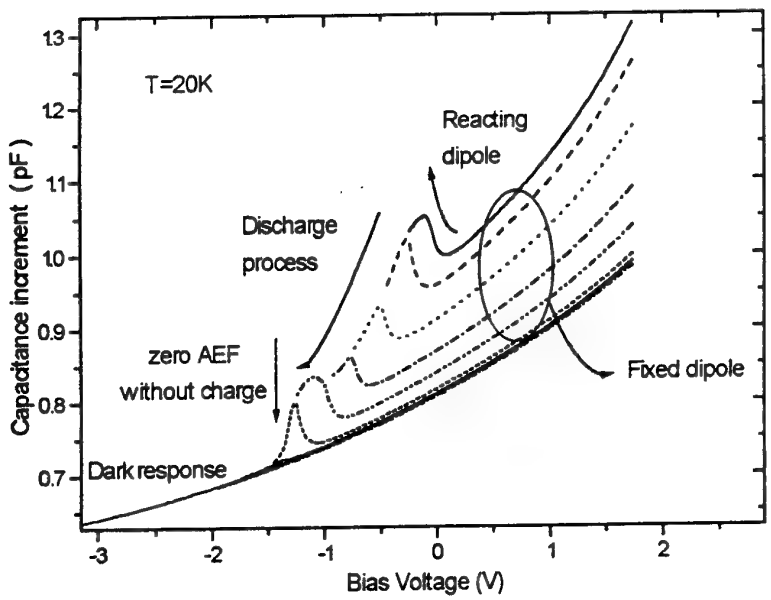

Figure 1. Capacitance-voltage characteristics after single charging pulse. Three regions are seen for each curve, corresponding to the fixed dipole, the reacting dipole and the discharge process.

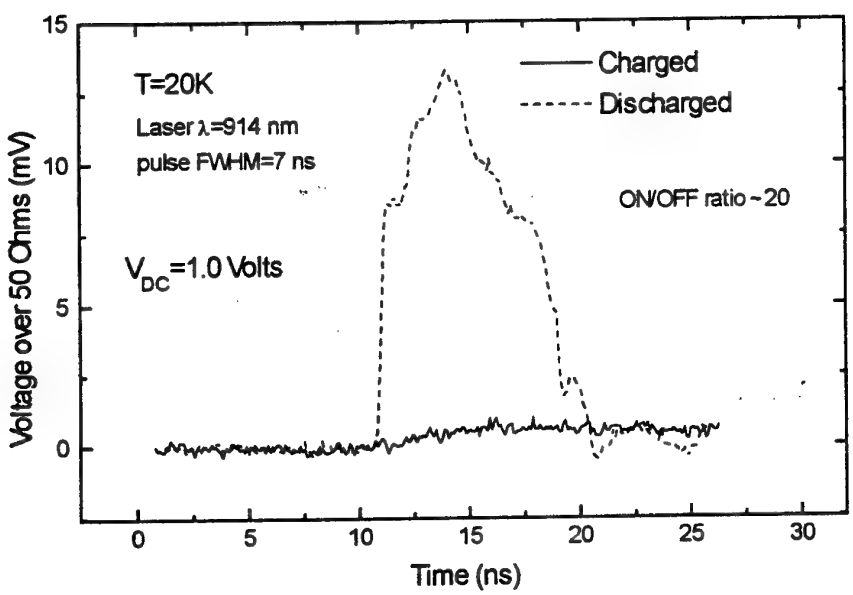

Figure 2. Time resolved Photocurrent for charged and uncharged states. The Blue shift of the absorption band edge for the charged state disables photocurrent.

Electronic states in QWs grown on high index surfaces

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The valence band determines the dependence of the electronic structure of layered semiconductors on the growth direction and on strain. Therefore, we have extended the eight-band **k**×**p** approach to calculate the band structure of strained semiconductor structures with arbitrary confining potential profile and for any crystallographic growth direction.

We find that the equal energy contours, confinement energies, effective in-plane masses and hole mixing largely depend on the direction of confinement giving new possibilities for valence band engineering, without the limitations imposed on layer thickness and material degradation encountered in strained structures.

Moreover, the relative intensity of interband transitions from heavy and light hole states can be tailored in this way, which is of importance for the performances of optical amplifiers.

CHARGE ACCUMULATION EFFECTS IN InGaAs/GaAs [111]-ORIENTED PIEZOELECTRIC MQW

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ABSTRACT

The influence of the design parameters on the electric field distribution, optoelectronic properties and structural assessment of strained [111]-oriented InGaAs/GaAs heterostructures are presented. In piezoelectric multiple quantum wells and superlattices, the electric field in the wells and barriers and the average electric field are deduced using simple analytical expressions. This allows to identify the samples with negative average electric field, which show some novel features associated with the photoinduced space-charge buildup, such as photoinhibition of the Quantum Confined Stark effect (fig. 1), multiple photoluminescence peaks at low temperature (fig. 1), transient displacement photocurrents , increase of the device capacitance (fig. 2) and blue shift of the absorption spectrum.

The dramatic influence of the charge accumulation effects on the behaviour of the samples with negative average electric field makes it difficult to assess the sample quality or structural parameters by optical or electro-optical techniques. High-resolution X-ray diffractometry has been applied to the structural characterization of samples with negative average electric field (fig. 3). This allow to determine period thickness, indium composition and degree of relaxation. These data together with capacitance-voltage measurements enable us to give an accurate estimation of the piezoelectric constant, e_{14}.

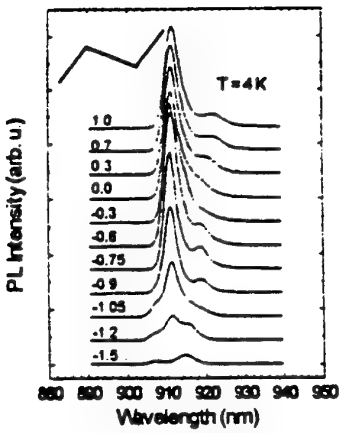

Fig. 1 Photoluminescence spectra in sample MN for various applied voltages (spectra shifted for clarity).

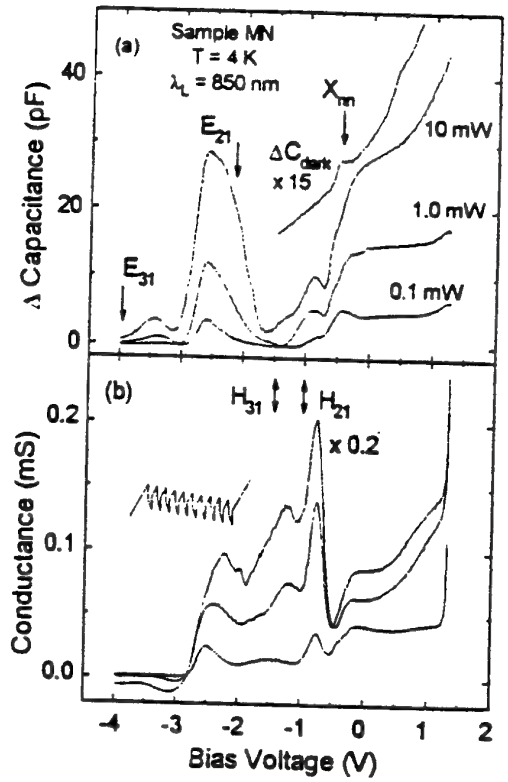

Fig. 2. Capacitance (a) and Conductance (b) in sample MN for three laser intensities. In (a) the capacitance under dark has been substracted, and the calculated resonance voltages are indicated with arrows. In (a) C_{dark} has been shifted downwards and enlarged. The conduction band profile at 0 V is shown in the inset (b).

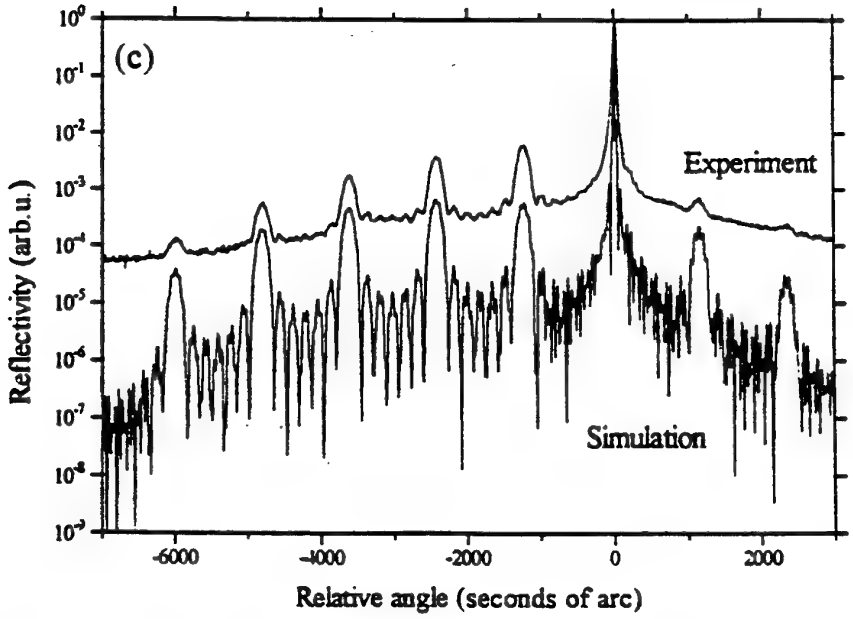

Figure 3. Experimental and simulated $\theta/2\theta$ scans of sample 332B. 333 symmetric reflection;

APPLICATION OF HIGH-RESOLUTION X-RAY DIFFRACTOMETRY TO THE STRUCTURAL STUDY OF EPITAXIAL MULTILAYERS ON NOVEL INDEX SURFACES

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ABSTRACT

The applicability of high-resolution x-ray diffractometry (HRXRD) to the structural characterisation of epitaxial structures on arbitrarily oriented surfaces is shown and discussed. This technique was used to study piezoelectric InGaAs/GaAs multiquantum well and superlattice p-i-n photodiodes grown on (111)B GaAs. The structural information obtained by HRXRD was necessary to understand the optoelectronic behaviour of the devices, since the strain-induced piezoelectric field strongly affected the photoluminescence and photocurrent spectra of the diodes [1].

The interpretation of the HRXRD experiments was possible thanks to a simulation model developed in our lab which allows the calculation of any symmetric or asymmetric reflection on a substrate with arbitrary orientation [2,3]. Therefore, the model can be applied to (11n) substrates as well as offcut (001) and (111) substrates. We show some theoretical and experimental examples of the influence of the substrate orientation, miscut angle, azimuthal orientation of the sample relative to the incident X-ray beam, and discuss the results within the context of the anisotropic elasticity theory and the dynamical theory of diffraction.

Figure 1 shows the HRXRD study of a 7 periods $In_{0.14}Ga_{0.86}As/GaAs$ MQW embedded in the intrinsic region of a p-i-n diode on (111)B GaAs. The agreement between the experiments and the simulations was very satisfactory in all the reflections, allowing the accurate determination of the period thickness, average In content, and capping layer thickness. Figure 2 points out the influence of the anisotropic distortion of the unit cell in pseudomorphic multilayers grown along a non-symmetry axis (in this case, on a (001) 3°-off GaAs substrate). This implies that the angular position of the MQW 0th order satellite and the split between adjacent satellites strongly depends on the miscut angle and the set of reflecting planes used.

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[2] A. Sanz-Hervás, A. Sacedón, E.J. Abril, J.L. Sánchez-Rojas, C. Villar, G. de Benito, M. Aguilar, M. López, E. Calleja, and E. Muñoz, *Adv. X-Ray Anal.* (1996) in press.

[3] A. Sanz-Hervás, M. Aguilar, J.L. Sánchez-Rojas, A. Sacedón, E. Calleja, E. Muñoz, E.J. Abril, and M. López, *Appl. Phys. Lett.* (1996) in press.

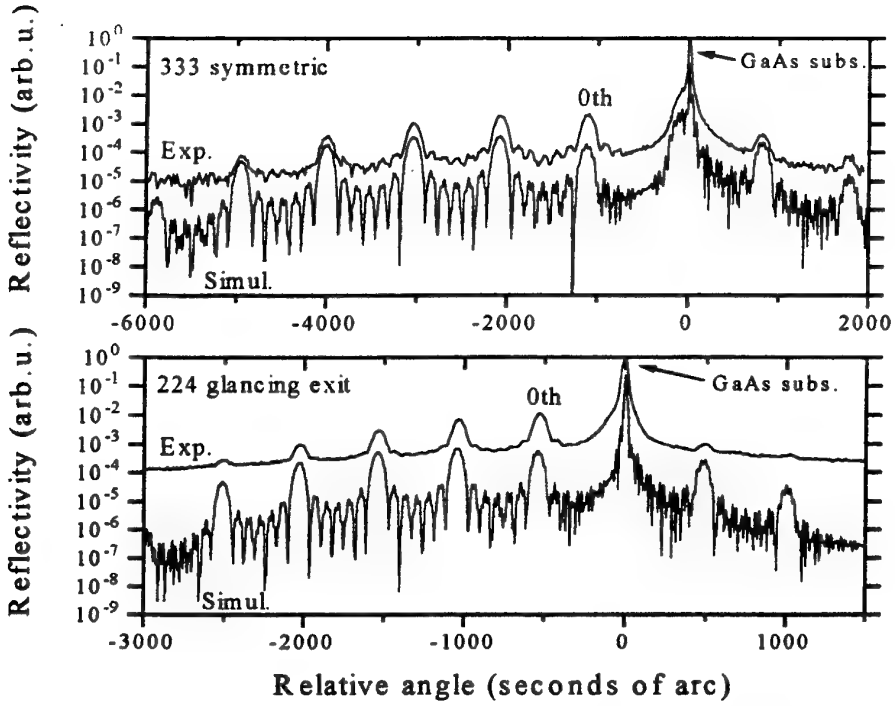

Figure 1. Experimental scans and simulations of a 7 periods InGaAs/GaAs p-i(MQW)-n diode on (111)B GaAs with a miscut angle of 1° towards [100]. The data deduced from the best fit were a period thickness $L_T = 232\pm3$Å, an average In content $\langle x \rangle = 6.76\pm0.05\%$, and a GaAs cap thickness $L_{cap} = 4100\pm25$Å.

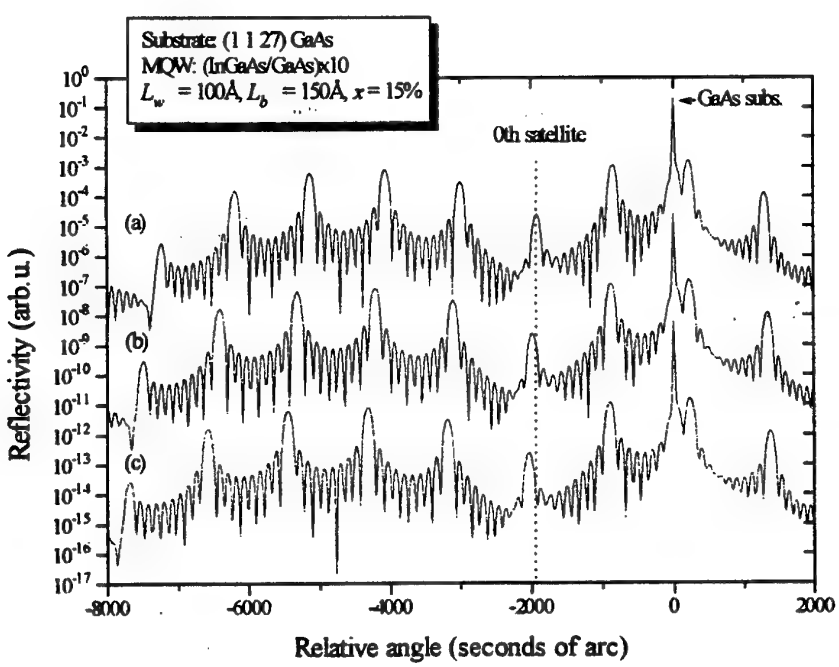

Figure 2. Calculated glancing incident reflections of a InGaAs/GaAs MQW on (001) GaAs with a miscut angle of 3° towards [110] (equivalent to (1 1 27) GaAs). In each curve the reflecting planes are: (a) (115); (b) (-115) or (1-15); (c) (-1-15).

Critical Thickness and Relaxation of (111) Oriented Strained Epitaxial Layers

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Growth on the <111> orientation brings with it new possibilities for nucleation and multiplication mechanisms for misfit relieving defects in epitaxial layers. Yet, despite these changes, the macroscopic relaxation behaviour of good quality InGaAs layers on <111> GaAs is remarkably similar to the relaxation behaviour of <001> oriented layers.

This again provides evidence that the final strain of a good quality relaxing layer is determined primarily by the layer geometry. Whilst considerations of dislocation morphologies and kinetics might be interesting, once it has been established that the relaxation behaviour is consistent with that occuring during 2D layer by layer growth, the final strain can be predicted simply from the layer thickness.

We present the full analysis of (111) oriented strained layers by high-resolution X-ray rocking curve analysis, showing the optimum data handling to derive strain and misfit. Data from partially relaxed layers are presented and compared with the behaviour of (001) layers. Results are compared with theoretical equilibrium critical thickness for the (111) orientation.

A study of the mobility anisotropy in front and back-gated (311)A hole gas heterojunctions

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(June 10, 1996)

This paper reports the fabrication of an in-situ back-gated hole gas on the (311)A surface of GaAs. The device consists of a normal MBE-grown two dimensional hole gas, optimised for low temperature transport, grown on top of a n-type doped GaAs back-gate. Devices were processed into a Hall bar geometry, using standard optical lithograhy techniques and a NiCr/Au gate evaporated onto the front of the sample. Utilising a combination of back and front gates the hole density could be varied from fully depleted to $2.1 \times 10^{11}\mathrm{cm}^{-2}$ with mobilities of up to $1.0 \times 10^{6}\mathrm{cm}^{2}\mathrm{V}^{-1}\mathrm{s}^{-1}$ at 1.7K.

It is well known the mobility of two dimensional hole gases fabricated on the (311)A surface of GaAs is anisotropic, with a higher mobility in the $[\bar{2}33]$ than the $[01\bar{1}]$ direction. By using either the front or back-gate we have been able to measure the mobility anisotropy as a function of carrier density. It is seen that at all carrier densities down to $< 2.0\times10^{10}\mathrm{cm}^{-2}$ the mobility in the $[\bar{2}33]$ direction is greater than that in the $[01\bar{1}]$ direction. Comprehensive measurements of the magnetoresistance at many different front-gate and back-gate biases in both crystalline directions are used to examine the extent of this anisotropy. In particular, whilst keeping the carrier density constant we are able to deform the hole gas wavefunction, moving the holes either up against or away from the heterointerface. This allows us to vary the amount of interface roughness scattering without altering scattering due to other mechanisms, thereby giving a direct measure of the contribution of the anisotropic interface roughness scattering to the mobility anisotropy.

Facet formation and characteristics of III-V structures grown on patterned surfaces

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In metalorganic growth technologies like *m*etal*o*rganic *m*olecular *b*eam *e*pitaxy (MOMBE) the surface selective chemical reactions of the precursors and the selective element incorporation is used for the localized growth of III-V semiconductor materials like GaInAsP/InP-heterostructures. Semiconductor surfaces are partly masked by non-semiconductor materials like SiO_2. The material growth is then localized to the open windows. In planar *s*elective *a*rea *e*pitaxy (SAE) there is only a single crystal plane as starting surface for growth. In consequence of the transitions from non-growth on the mask to growth on this single semiconductor plane, higher index crystal planes are formed in this transition zone. These planes always represent the lowest growing planes, meaning that the growth on these planes is limited by kinetic reactions, desorption, surface and interfacet diffusion processes. These processes do depend on the chemical elements and molecules so that the material composition on such higher index transition facets is a clear function of the material growth. Particularly for ternary (GaInAs) and quaternary (GaInAsP) materials a significant dependence on the material composition and growth rate is detected due to molecule dependent surface diffusion and desorption. The stable formation of $(01\bar{1})$ side facets on partly masked (100) surfaces having a miscut allows for in-situ produced lateral heterostructures forming rectangular junctions to vertical structures. In embedded SAE a recess area is etched in the open windows yielding tubs formed by several crystal planes. Such arrangement allows for lateral coupling of heterostructures where the various crystal planes are directly offered as starting surface for growth.

The contribution will give examples of sharp lateral material transitions in planar and embedded SAE based on the mechanistic insights in facet formation and growth on patterned surfaces. These lateral structures can be utilized for the fabrication of low dimensional systems and the lateral integration of heterostructure devices.

Transport and Optics in Quantum Wires Fabricated by MBE Overgrowth on the (110) Cleaved Edge

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A. Pinczuk, W. Wegscheider, and K. W. West

The MBE double-growth technique we call Cleaved-Edge-Overgrowth has over the past several years proved itself to be especially suitable for making quantum wires of the very highest quality. We will review our recent progress in measuring the transport and quantum optics characteristics of these wires, and the MBE growth issues that arise with Cleaved Edge Overgrowth fabrication.

Our transport experiments have resulted in 250Å wide quantum wires with ballistic mean free paths exceeding 10 microns. We verify the prediction that in the ballistic regime the electron conductivity in a quantum wire is independent of the wire length, and shows quantized steps proportional to e^2/h. The deviation of our observed step heights from exactly e^2/h is taken as evidence for correlated electron behavior.

The electrons are tightly confined on three sides by atomically smooth GaAs/AlGaAs heterojunctions and in the fourth direction by an electric field. This results in a quantum wire of nominal square cross-section 250Å by 250Å. Magneto-transport measurements reveal quantum wire subband seperations in excess of 20meV as well as the symmetries of the wavefunctions of the 1D modes. For optics studies our quantum wires are made using Cleaved Edge Overgrowth to form a line junction as two qunatum wells are made to intersect with the cross-section forming a letter "T". We have shown that this line intersection seperately forms a quantum wire bound-state for holes, for electrons, and even for excitons. We have characterized our optical wires by PL, by PLE, and by scanning near-field optics.An important application of this work is our demonstration of the first quantum laser using this T-geometry.

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Strain distribution in quantum wires fabricated by MBE overgrowth on the (110) cleaved edge of a strained superlattice.

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Here we consider "quantum wires got from strain-induced lateral confinement". Such systems have been first proposed in Ref. [1]. They result from a two steps growth process. During the first step a strained superlattice is deposited on a substrate along the [001] direction. The sample is then cleaved. The second step is the growth of three layers (a quantum well sandwiched between two barriers) above the [110] cleaved interface. Such structures have been first grown with III-V systems [1], and more recently with CdTe-CdZnTe layers, the superlattice being strain-compensated [2]. In such systems, the strain present in the superlattice is generally supposed to induce lateral confinement in the [110] quantum well resulting from strain modulation in the in-plane lattice constant of the overgrown quantum well. From this lateral confinement should result the existence of quantum wires. Photoluminescence studies clearly show a signal which originates from the area above the superlattice, and due to the presence of the quantum well [3], which is usually considered as a "PL wire signal".

We have calculated the strain distribution in such II-VI structures using the valence force field approximation(Keating's formulation).

First, far away from the "lateral surface" (the [001] surface got from the first growth step), we show that the strain modulation is totally attenuated in the [110] quantum well : the atom elastically rearrange, such a way to equally distribute the strain in the [110] quantum well. This result, similar to the one of ref. [4] got from continuous elasticity, does not support the formation of quantum wires in the CdTe quantum well region, due to strain-induced modulation from the superlattice.

At the opposite, when one considers the strain distribution near the lateral surface, one gives evidence of a strong "edge relaxation": in the vicinity of the lateral [001] surfaces one observes strong variations of the local deformations. It is interesting to note that this edge relaxation does not depend on the presence of the superlattice (for the considered sample, as far as it is "strain compensated"). Moreover the decay of the strain relaxation from the surface to the core of the sample appears to be rather slow. From this edge relaxation could result the possibility to have a very broad and smooth "surface quantum wire" which could perhaps explain the "PL wire signal".

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30 may 1996, submitted to NIS'96

RHEED and STM study of two dimensional growth of InAs on GaAs 111A surfaces

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Despite its importance in device applications, the ability to obtain high quality epitaxial growth of highly mismatched systems of compound semiconductors is hindered by the formation of three dimensional (3-D) islands, at least for growth on (001) oriented substrates. This process is usually attributed to total surface energy minimization effects and several attempts have been made to overcome the problem by controlling the kinetics and/or energetics of the surface processes which govern the formation of 3-D islands via the Stranski-Krastanov mechanism. The approach we propose here is to influence the growth mode through the use of non-(001) surfaces. The choice of a particular substrate orientation will determine the strain relaxation mechanism. This will not only change the energetics of surface reconstruction and steps, but also the kinetics of adsorption, migration and desorption. In this paper, we present the results from in-situ reflection high energy electron diffraction (RHEED) and scanning tunneling microscopy (STM) observations of the growth mode of InAs on GaAs (111)A substrates during solid source molecular beam epitaxy (MBE). In contrast to the 3-D growth mode observed on GaAs (001) substrates, there is no evidence for 3-D island formation on the (111)A surface.

Figure 1 shows the RHEED patterns obtained for deposition of 1,2, and 3 MLs of InAs on a GaAs (001) surface. The growth mode change from 2-D to 3-D between 1 and 2 MLs is evident from the appearance of transmission spots in the RHEED pattern. This is simply a manifestation of Stranski-Kranstanov growth and has been reported by many previous authors. However, for growth on (111)A substrates, the behavior is quite different and a streak pattern is maintained (Fig.2). This result confirms that growth occurs without transition to the Stranski-Kranstanov mode, and no 3-D island is formed. This allows us to use non-(001) substrate to clarify the strain relaxation mechanism in the early stages of heteroepitaxial growth with STM observations. Figure 3 shows the STM images of GaAs (111)A surfaces after the depostion of 2 and 5 MLs of InAs. The surface is atomically flat for both surfaces showing no 3-D growth. After 2 MLs deposition, the coalescence of strained islands to form misfit dislocations at their boundaries is clearly visible. At 5MLs deposition, a network with trigonal symmetry is confirmed. The dark contrast of the network is attributed to the strain fields induced by the misfit dislocations at InAs/GaAs interfaces. An atomic model for the dislocation network is proposed to explain the formation of misfit dislocations and stacking faults which are buried at the heterointerfaces. Furthermore, atom-resolved STM imaging has allowed us to study the threading segments of the dislocations. The detailed mechanism of dislocation formation and strain relaxation will be discussed based on the STM imaging of these misfit dislocations.

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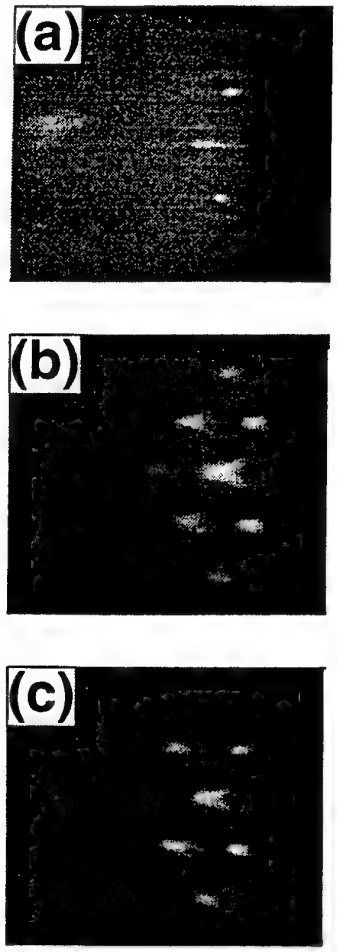

Fig.1 : RHEED patterns obtained with [1$\bar{1}$0] azumith after the growth of (a) 1.0 (b) 2.0, and (c) 3.0 MLs of InAs on GaAs (001) surfaces.

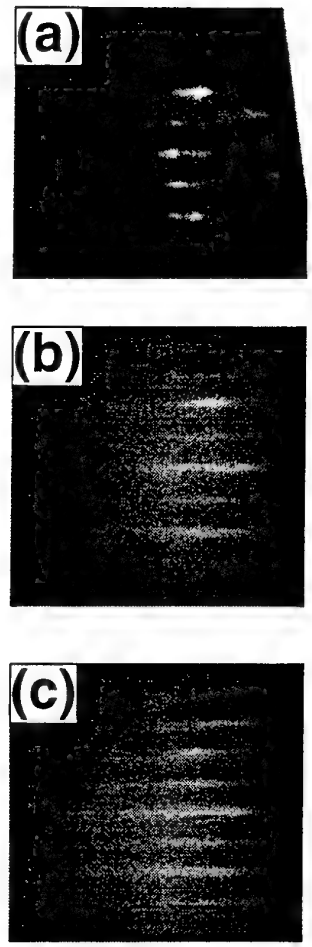

Fig.2 : RHEED patterns obtained with [1$\bar{1}$0] azumith after the growth of (a) 1.0 (b) 2.0, and (c) 3.0 MLs of InAs on GaAs (111)A surfaces.

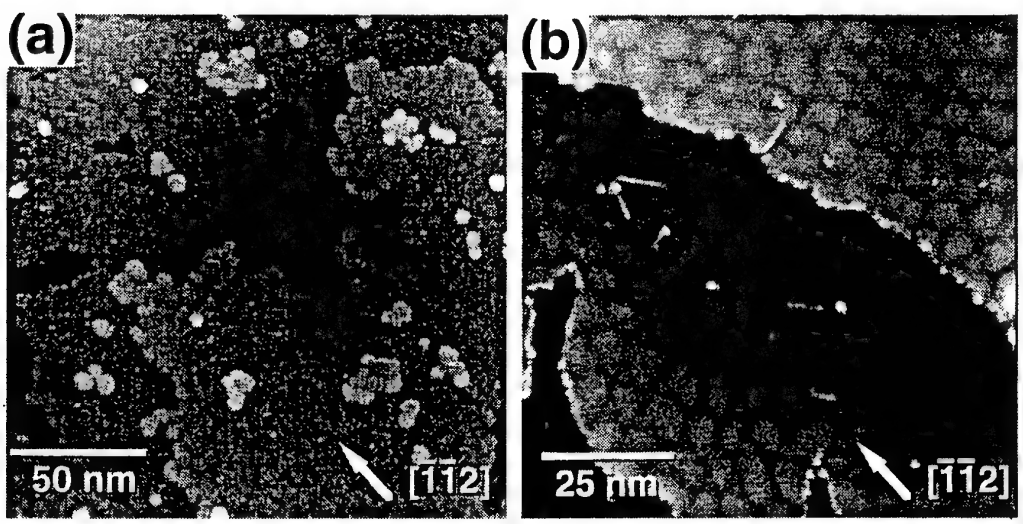

Fig.3 : STM images of (111)A surfaces after the growth of (a) 2.0 and (b) 5.0 MLs of InAs on GaAs.

As_2 and As_4 incorporation kinetics on the GaAs(110) surface: implications for growth and doping

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Reflection high energy electron diffraction (RHEED) intensity oscillations were used to obtain the As_2 and As_4 incorporation coefficients for GaAs(110) homoepitaxy by molecular beam epitaxy (MBE). In both cases, the incorporation coefficient decreases with temperature, with values obtained for As_2 being approximately twice those of As_4. The arsenic incorporation coefficients were also much smaller than those obtained on the (001) surface. Therefore, with the same As/Ga flux ratio calibrated on GaAs(001) surface, the effective As/Ga flux ratio during homoepitaxial growth of GaAs(110) is actually smaller. In addition, it is different for layers grown using As_2 and As_4 and is also temperature dependent.

The variation of the arsenic incorporation coefficients with growth temperature was modelled by assuming that the arsenic incorporation is a precursor mediated process, and in both cases, involves a molecularly adsorbed As_2* intermediate. The difference in the activation energies for the desorption and incorporation of this As_2* intermediate was found to be the same when using either As_2 or As_4. Since the RHEED intensity oscillation technique is a measure of the formation of GaAs, only the final step leading to growth depends on the incorporation of arsenic from this intermediate. The implication is that the mechanism involved in the final incorporation of As to form GaAs is independent of the arsenic species used.

As GaAs(110) homoepitaxy is very sensitive to growth conditions, abnormally high As/Ga flux ratio (~18:1) and low temperature (~450°C) are required to obtain layers exhibiting smooth surface morphology. On the contrary, layers grown using a lower As/Ga flux ratio or a higher growth temperature yield poor surface morphology. In the smooth layers, silicon (Si) dopant atoms show uncompensated n-type behaviour whilst in the layers with poor morphology the Si dopant becomes progressively compensated. Assuming that silicon site occupation on the (110) surface depends on the competition between Si and the impinging Ga and As atoms, a low As coverage will enhance incorporation of silicon to As sites and increases the Si acceptor concentration. This will partly compensate the Si donor concentration and give rise to a compensated n-type material. A lower As coverage will also encourage build up of excess Ga on the surface and therefore degrade the surface morphology.

The kinetic results are consistent with these morphological and doping studies of the growth of GaAs on GaAs(110) using As_2 or As_4. Growth morphologies and Si doping show very similar trend with growth conditions and the same growth regimes (i.e. monolayer-by-monolayer, bilayer-by-bilayer, step flow and Ga-induced roughening) have also been identified using RHEED. This similarity suggests that the ***effective As population*** is the important parameter, and it remains the same for As_2 and As_4 as the intermediate As_2* is common to the kinetics in both cases.

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Anisotropic surface diffusion at crystal facet transitions during localized Ga-In-As-P growth by MOMBE

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The localized growth of device or low dimensional structures by selective area epitaxy (SAE) forms intrinsically various facets at the transition between growth and non-growth areas. Therefore crystal surfaces with variable orientations are simultanously formed and overgrowing. This work presents the effects on the surface diffusion at the edges of these facets at InP/InGaAsP/InP structures grown by metalorganic molecular beam epitaxy (MOMBE).

We have selectively grown semiconductor ridges in SiO_2 mask windows with widths ranging from 1.5 to 250 µm. The ridges were characterized by Nomarski interference microscopy, scanning electron microscopy (SEM), alpha-step measurements and spatially resolved photoluminescence (µ-PL) measurements at 300 K. We have systematically investigated the effects of varios step types and step densities of the misoriented (100) InP substrates, the growth temperature and the V/III input ratio on the structure of the semiconductor ridges.

The observed anisotropic surface diffusion is a consequence of an increased trapping probability of the molecules at the surface steps in the upstairs direction. The anisotropic surface diffusion during the localized growth is leading to a change of the shape of the ridges, the material composition at different facets and the formation of a surface corrugation as found earlier [1].

Due to the surface diffusion processes the growth rate of the ridge sidewalls depends on the growth direction, and on the width of the ridges. The surface of the narrow ridges is tilted and this tilt is decreasing for lower step densities. For the simultanous growth on different facets not only the growth rate is different, but also the material composition variies from (100) facet to the sidewall facets of the ridges. This will be shown by µ-PL measurements.

The SEM cross-section view in Fig. 1a shows a typical ridge at the semiconductor mask transition. The surface corrugation is weakly visible. This corrugation can be clearly observed in the interference micrograph in Fig. 1b. This surface corrugation only exists at a sharp transition from a growth to a non-growth area, e.g. at the edge of a dielectric mask, at defects or scratches on the surface or at cleaved edges, in the direction of the B (chemical reactive surface) steps downstairs.

For higher step densities of the substrate surface the depth of the surface corrugation is increasing and the distances between the maxima and minima are reduced. This distances are shortened for decreasing mobility of the molecules on the surface due to lower growth temperatures or higher V/III ratio, too.

We have simulated this planar selective area growth of ridges in a model. The solution of the nonlinear partial differential equation is plotted in Fig. 2 with the solid line. This simulation agrees well with the observed surface corrugation in the micrograph or the alpha-step measurement plotted with the dashed line in Fig. 2.

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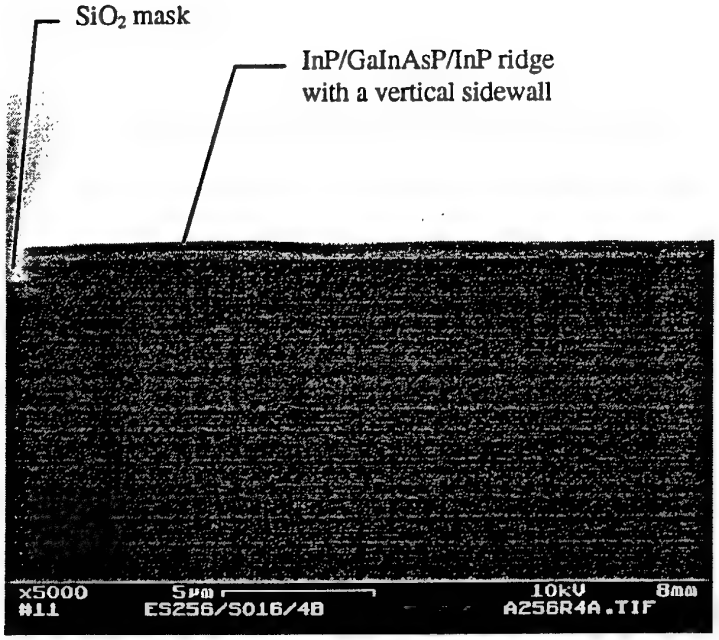

Fig.1a: SEM cross-section view of a typical InP/GaInAsP/InP ridge

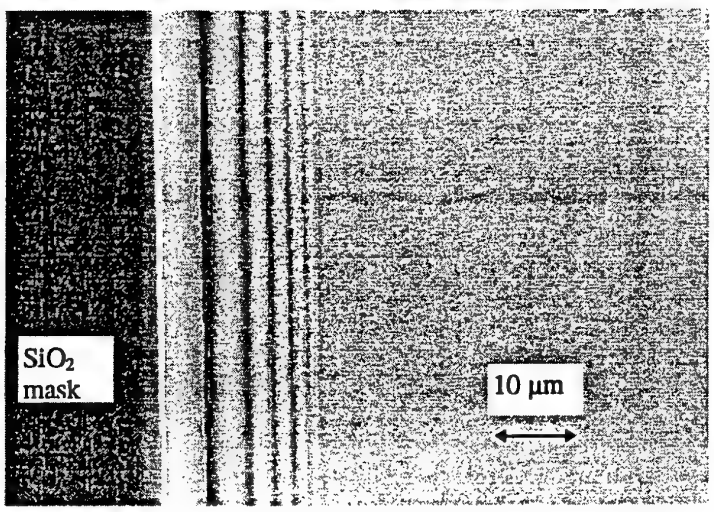

Fig. 1b: Micrograph of the surface corrugation at the semi-conductor mask transition for B steps in the down-stairs direction

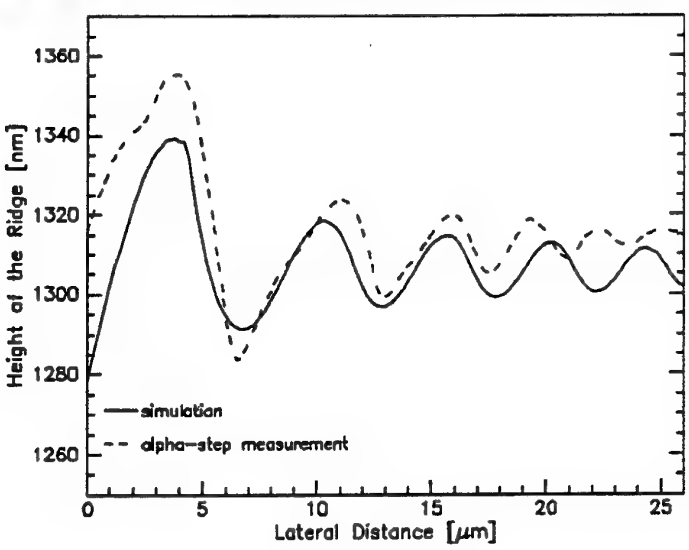

Fig. 2: Surface corrugation of the height of the ridge versus the distance to the mask for the simulation and the alpha-step measuremen

Effects of Tensile Strain and Surface Steps on Epitaxial Layer Morphology of CBE Grown GaInAs/InP Multiple Quantum Well Structures

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We present investigations of the effect of tensile strain and surface off-orientation on the epitaxial layer morphology of GaInAs/InP multiple quantum well (MQW) structures. The structures were grown by Chemical Beam Epitaxy (CBE) and consisted of 10 periods of 5nm $Ga_xIn_{1-x}As$ / 4.5nm InP /1 monolayer (ML) InAs / 4.5nm InP MQW structures with x_{Ga} up to 0.77. This corresponds to a lattice mismatch of $(\Delta d/d)^{\perp} = -4.2\times10^{-2}$ in the GaInAs layers. The InAs-ML was deposited to provide partly a strain compensation of the tensile strained GaInAs layers. The InP (100) substrates were either exactly oriented or 2° off oriented towards [110]. In each growth run both substrate orientations were used.

The structures were investigated by double crystal X-ray diffraction (XRD) and cross-sectional transmission electron microscopy (TEM). The thickness of the individual MQW layers as well as the Ga concentration in the GaInAs layers was obtained by comparing the XRD rocking curves to dynamical simulations using the simulation package RADS (Bede Scientific, U.K.).

Cross sectional TEM reveals that for $x_{Ga} = 0.77$ vertically aligned thickness fluctuations of the GaInAs layers are present (Fig.1). These undulations are parallel to the $[01\bar{1}]$ direction (Fig.1, left) and have a periodicity of approximately 25nm. The undulations are amplified with increasing number of periods and tend to evolve into well defined facets of the {411} type. Parallel to [011] (Fig.1, right) no undulations are present. The same features are observed for both exactly and off-oriented substrates. The growth surface is smoothened by the subsequent lattice matched InP layers. This smoothening effect of the InP can easily be seen due to the InAs strain compensation layer within the InP layers in Fig.1.

For $x_{Ga} = 0.66$ ($(\Delta d/d)^{\perp} = -2.6\times10^{-2}$) and exactly oriented substrates sharp quasi 2-dimensional interfaces between the respective MQW layers are observed in both cross sections (Fig.2). This shows that the undulations appear only above a critical strain value.

Structures grown on off-oriented substrates, however, show an additional feature. For $x_{Ga} = 0.66$ a strain induced step bunching instability is observed (Fig.3). In contrast to the undulations the macrosteps are created parallel to the surface steps. This means that the macrosteps are visible in $[01\bar{1}]$ (Fig.3, left) as well as [011] cross section (Fig.3, right) for the chosen off-orientation. The distance and height of the macrosteps correspond to the substrate off-orientation angle. The presence of the macrosteps leads to an earlier onset of the thickness undulations (Fig.3, left). For higher x_{Ga} undulations as well as macrostep formation is observed.

To our knowledge, this is the first time that both features are independently observed in one sample type. Our results show that two different strain induced mechanisms are involved in the generation of the undulations and the step bunching. We discuss these mechanisms with respect to experimental [1, 2] and theoretical [3] studies.

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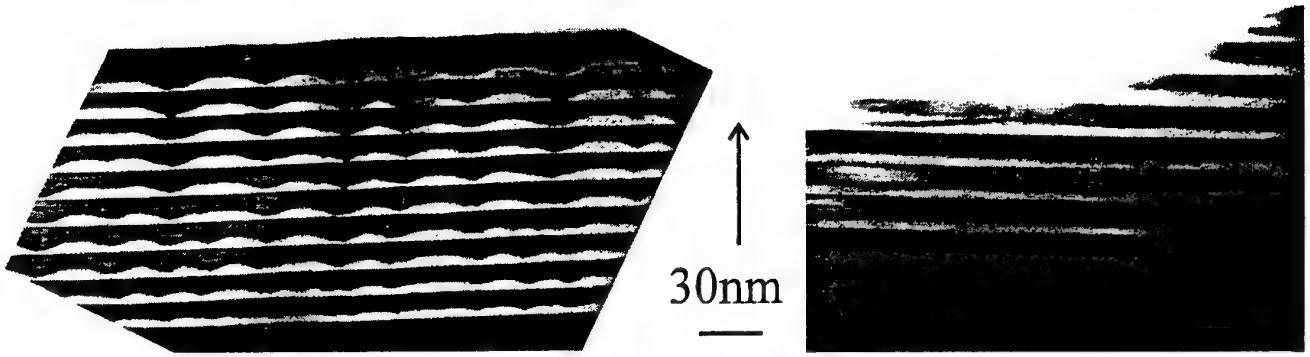

Fig.1 Cross-sectional TEM micrograph of a 10 periods GaInAs/InP MQW with $x_{Ga} = 0.77$ grown on a (100) exactly oriented InP substrate. Left: [01$\bar{1}$] cross section, right [011] cross section. The GaInAs layers appear bright, the InP layers dark. The arrow marks the growth direction.

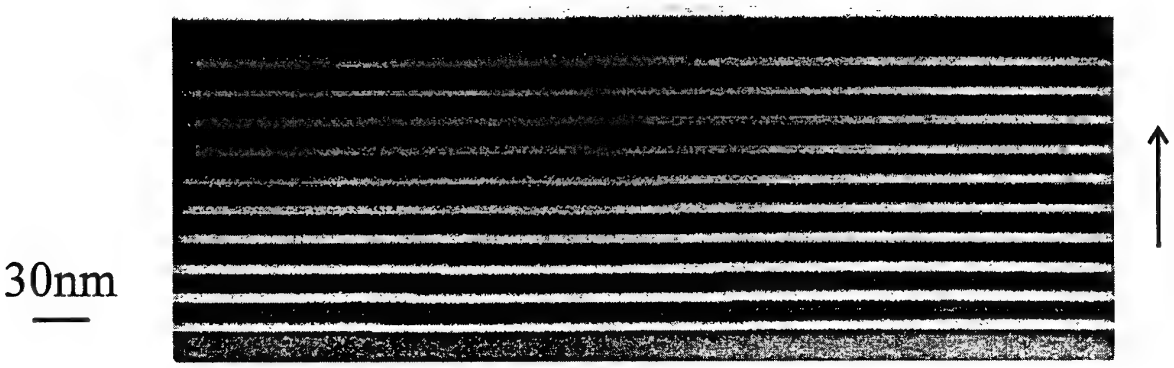

Fig.2 Cross-sectional TEM micrograph of a 10 periods GaInAs/InP MQW with $x_{Ga} = 0.66$ grown on a (100) exactly oriented InP substrate in [011] cross section. The GaInAs layers appear bright, the InP layers dark. The arrow marks the growth direction.

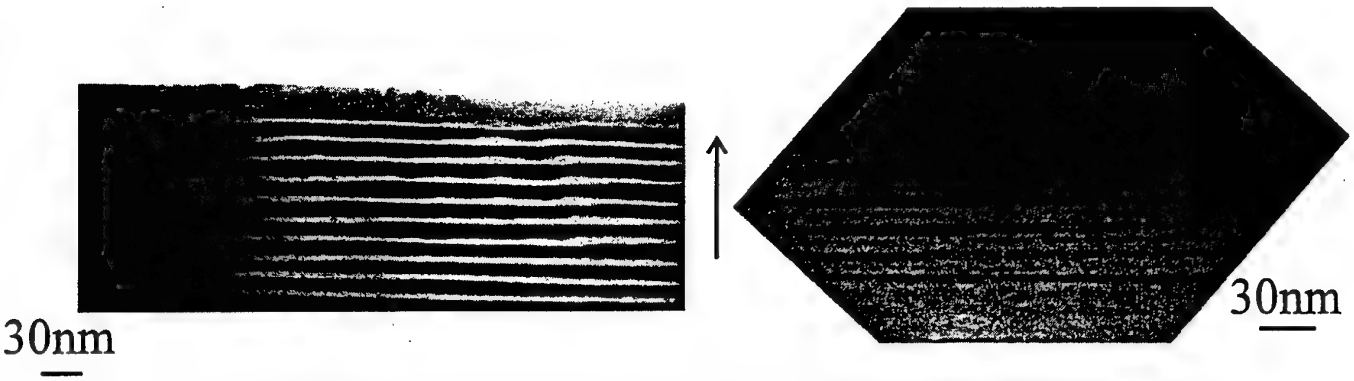

Fig.3 Cross-sectional TEM micrograph of a 10 periods GaInAs/InP MQW with $x_{Ga} = 0.66$ grown on a (100) InP substrate 2° off towards [110]. Left: [01$\bar{1}$] cross section, right [011] cross section. Left picture: GaInAs layers appear bright, InP layers dark. Right picture: GaInAs layers appear dark, InP layers bright. The arrow marks the growth direction.

InAsP/GaInP strained multilayers grown by MOVPE on (001), (113)B and (110) InP substrates : the role of the surface characteristics

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Zero-net strained multilayers alternating GaInP and InAsP with lattice mismatches of -1% and 1% respectively have been grown by Metal-Organic Vapor Phase Epitaxy on different InP substrates. The growth conditions are similar with a growth temperature of 610°C. The samples have been investigated by Transmission Electron Microscopy to study the influence of the growth surface on the growth morphology.

* On a (001) substrate, the GaInP and InAsP layers are laterally modulated, forming vertical stripes parallel to the [1-10] direction, thus balancing the mismatch along the [110] direction rather than along the [001] growth direction. The lateral period along [110] is around 0.12 μm [1].
* On a (113)B substrate, a similar modulation is observed, the stripes being elongated along the [3-3-2] direction. The lateral period along [110] is close to 0.1 μm.
* On a (110) vicinal substrate (misorientation of 3° towards (111)B), a different behavior is observed : the growth surface is made of (111)B macrosteps separated by exact (110) terraces. A great density of defects is associated to the macrosteps.

The modulation observed for (001) and (113)B substrates was accounted for by elastic relaxation of the strained layers. The stripes orientations are discussed in terms of surface characteristics, and can be related to the surface reconstruction. For the (001) substrate, the facets forming the stripes are systematicaly of the A type (gallium steps). On the other hand, for the (113)B one, although the resulting facets are mixed (Gallium and Arsenic steps), the part of B type (arsenic steps) is due to the initial substrate orientation, while the part of A type (gallium steps) is due to the modulation. In both cases, only A type facets are spontaneously developped. As they are (i) parallel to [1-10], (ii) made of gallium steps, the A type facets are highly compatible with the surface reconstructions, wich usually needs (i) dimerization of the group V elements along the [1-10] direction and (ii) extra dangling bonds of group III elements to ensure the local neutrality.

The morphology observed on the (110) substrate seems rather related to a step bunching phenomena, of with the origin is unclear.

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SELF ORGANIZATION OF QUANTUM WIRE-LIKE ON $In_xGa_{1-x}As$ SINGLE QUANTUM WELLS GROWN ON (100) InP VICINAL SURFACES DEPENDING ON THE SUBSTRATE MISORIENTATION, BUFFER MISMATCH AND GROWTH TEMPERATURE.

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Nowadays the assessment of the formation mechanism of self-low-dimensionality structures as quantum wires and dots is subject of a great interest due to the promising device applications of the electronical and optical properties induced by current and energy state quantization of confined carriers. Even more, since this spontaneous configuration may avoid the problematic and high cost of the technological procedures needed to configure such reduced designs.

In this work, using Transmission Electron Microscopy (TEM) and X-ray Diffraction (XRD) we analyze the spontaneous appearance of a lateral composition modulation on the $In_yAl_{1-y}As$ buffer layers of high electron mobility transistors (HEMT) giving rise to a self-induced quantum-wire like morphology on the $In_{0.53}Ga_{0.47}As$ single quantum wells grown over the buffer. The growth of the samples was carried out on exact and vicinal 4°off (100) towards (111) InP surfaces. Both oriented and misoriented samples were grown at the same run in order to avoid additional possible contributions to their final morphology than the misorientation itself.

The structure of the analyzed samples is 5nm GaAs/50nm $In_{0.52}Al_{0.48}As$/18nm $In_{0.53}Ga_{0.47}As$ (SQW)/ 2μm $In_yAl_{1-y}As$ buffer layer/InP, with $y_{In} \simeq 50\%$. The cross-section TEM g=200 images along $\langle 011 \rangle$ diretions reveals an asymmetrical rippling of the well. The undulation is also evident in the lower InGaAs/InAlAs interface, indicating that the inhomogeneous growth must have been induced below in the buffer. The origin of the undulation is revealed in g=022 and 111 images for which a contrast modulation appears crossing the whole epilayer, with dark-bright bands at an angle of $\simeq$13-15° with respect to the growth direction, well correlated with the valleys and ripples of the surface roughness. These domains correspond to In-rich and Al-rich domains oriented closed to the planes {133} and {122}.

The appearance of such lateral composition modulation is discussed according to the influence of the growth temperature, varied in the range 530°C-580°C, the tensile strain of the $In_yAl_{1-y}As$ buffers (y_{In} in the range 48-50%) and the substrate misorientation. TEM results of samples grown on exact (100) and 4°off InP surfaces, have revealed the influence of the misorientation steps and high growth temperature on the development of In-rich/Al rich lateral domains. XRD has confirmed the contribution of the lateral modulation to strain accommodation in tensile layers. These domains also induce a lateral modulation and rough growth in the upper InGaAs well, leading to a quantum wire-like spontaneous structure.

Self-organization of microstructures on high-index semiconductor surfaces (Invited)

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In order to directly control the size and in particular the position of nanostructures naturally formed on high-index semiconductor surfaces during MBE [1] and MOVPE [2] we investigate the selectivity of growth on patterned high-index surfaces. During MBE of (AlGa)As on patterned GaAs (311)A substrates we find a new phenomenon in the selectivity of growth to form a fast growing sidewall on one side of mesa stripes oriented along the [01-1] direction [3]. Preferential migration of Ga atoms from the mesa top and bottom towards the sidewall develops a smooth convex curved surface profile without facets. This unique growth mode that does not occur for the perpendicular stripe orientation nor on other patterned GaAs (n11)A&B substrates is stable for step heights down into the quantum size regime to produce lateral quantum wires on patterned GaAs (311)A substrates. Quantum confinement of excitons in the wires is demonstrated by the transition from one-dimensional to magnetic confinement with increasing magnetic field. Finally, the wires can be stacked in growth direction without any increase in interface roughness or wire size fluctuations indicating a self-limiting lateral growth mechanism.

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Abstract for NIS 96

Direct Synthesis of Quantum Dots for Single-Electron Transistors and Laser Diods

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In this contribution we present new results on the direct synthesis of nanostructures by combining an epitaxial growth technique like molecular beam epitaxy with prepatterning of the substrate wafers. A second technique is based on the island formation in strained layer heteroepitaxy. Quantum dots with dimensions of only a few atomic distances have been realized this way. An important point is, that the size of the structures is controlled within the epitaxial deposition in a self adjusting process.

A novel concept to realize a single quantum dot inluding self-aligned tunneling junctions to electrical leads by epitaxial growth on patterned GaAs substrates is presented. One growth process is sufficient to create a compact single-electron transistor tunable with a voltage on a single gate which is also fabricated within the epitaxial growth. Transport measurements reveal that the self-organized dot can be charged and discharged with single electrons. The conductance through the dot versus the voltage applied on the gate show periodic oscillations up to 5.9 K. Increasing the voltage from one conductance minimum to the next increases the electron number within the dot by one due to the small capacitance. At 22mK clearly resolved conductance peaks, separated by regions of zero conductivity (Coulomb blockade) are observed.

Self assembling quantum dots are prepared by Stransky Krastanov growth of InP on a GaInP buffer layer lattice matched to the (100) GaAs substrate. The InP islands evolve after deposition of 1.5 monolayers. The energy of the InP quantum dot related photoluminescence peak shifts from 1.85 to 1.53 eV as the nominal InP thickness increases form 2 to 10 monolayers. Optically pumped AlInP/GaInP laser structures with InP quantum dots are investigated. Laser action is observed from both the InP wetting layer at 1.85 eV and the quantum dots at 1.76 eV. The quantum efficiecy above threshold is much higher for the quantum dots.

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Formation of InP-Based Quantum Structures by Selective MBE on Patterned Substrates Having High-Index Facets

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In view of applications to next-generation electronic and optoelectronic devices, various approaches for nanostructure formation are being intensively studied. Among them, selective MBE growth on mesa-patterned substrates having high-index facets appears to be particularly promising due to capability of size reduction without process-induced damage and to formation of smooth facets. As compared with MBE growth using patterned SiO_2 or Si_3N_4 masks, which usually requires irradiation by atomic hydrogen for successful growth, this approach is much simpler and more versatile and can be done using a standard MBE system. So far, it has been applied mostly to the AlGaAs/GaAs system.

This paper presents and discusses results of a systematic study to clarify the growth conditions for successful formation of InP-based InGaAs/InAlAs quantum wires and dots by selective MBE growth on mesa-patterned (001) InP substrates. This material system is more suitable for realizing high temperature operating quantum devices due to its large conduction band discontinuity and superb electron transport.

First, selective MBE growth experiments of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ wire and dot structures on patterned (001) InP substrates are discussed generally. 7 different mesa patterns were prepared along <$\bar{1}$10>, <110> and <100> directions on (001) InP substrates, using photolithography and wet chemical etching. Saturated Br-water (SBW) solution or HBr solution was used for etching. Then, in order to clarify growth mode and selectivity, multi-layer structures consisting of InGaAs and InAlAs layers were formed on the patterned substrates by alternate growth in a standard MBE system. Planar InP substrates were placed next to the patterned substrates as reference. The resultant wire and dot structures were characterized in terms of structural uniformity and growth selectivity based on SEM observation. Based on such criterions, wire formation in <$\bar{1}$10> and <100> directions and dot formation on pedestals with (201) sidewall facets were shown to be appropriate.

Then, a particular attention will be paid on successful growth and characterization of <$\bar{1}$10> oriented InAlAs/InGaAs ridge quantum wires. Growth of InGaAs buffer layer on <$\bar{1}$10> oriented InP mesa-stripes produced ridge structures having (311)A facets. Further growth of InAlAs/InGaAs/InAlAs on this ridge structures under appropriate conditions results in an array of arrow-head InGaAs quantum wires (QWRs) bounded by (311)B and (411)A facets of InAlAs. The size of the wire is independent of the original lithographic pattern and is solely dependent on the growth conditions. The QWR array gave strong cathodoluminescence (CL) and photoluminescence (PL). Monochromatic CL study confirmed that the luminescence comes from the QWR itself. The QWR array gave intense and narrow PL emission which was observable up to room temperature.

Magneto-transport measurements were made on a single wire by forming Au-Ge-Ni Ohmic contacts on both ends. A clear Shubnikov-de Haas oscillation was observed. From this, a non-linear Landau plot was obtained, indicating one-dimensional transport. Fitting with a parabolic potential model, a zero bias wire width of 95 nm, linear electron density of 1.6×10^7 cm^{-1} and a level spacing of 10 meV were obtained. This level spacing is much larger than the values of 1-3 meV typically found for GaAs-based split-gate wires, showing a much higher confinement potential in the present QWR. A QWR transistor having a Pt/Au Schottky gate showed an excellent gate control and showed near pinch-off clear Coulomb blockade (CB) oscillations and Coulomb gaps at low temperatures up to about 50 K.

GaInAs/InP quantum wires grown by metalorganic vapor phase epitaxy on V-grooved InP substrates

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In the past few years a lot of work has been spent in the development of fabrication techniques for high quality quantum wire structures. Methods which rely on the direct formation of quantum wires like cleaved edge overgrowth or growth on nonplanar substrates were developed. Especially the growth in V-grooved substrates is a common used technique. Wires defined by post growth etching or ion implantation have the disadvantage of unavoidable damages in the active layer while directly grown structures are free of defects.

In the GaAs/AlGaAs system quantum wire lasers with very low threshold currents have been grown and fabricated onto V-grooved substrates. Much less progress has been made on InP-based materials. In contrast to the GaAs/AlGaAs growth no resharpening of the V-groove during the MOVPE growth of InP has been observed. Therefore, it is of great importance to prepare the V-grooves with etching techniques which require no or only a very thin buffer layer for epitaxial growth. Another problem in the GaInAs/InP system is the lattice mismatch which results from a different migration behavior of the In and Ga species in the V-groove.

In our experiments (100) InP substrates were covered with 100nm SiO_2 and standard photolithography was used to realize [0-11] oriented stripe fields in the µm-range. For further reduction of the dimensions down to 200nm width and 450nm period electron beam lithography was employed. V-grooves with $(111)_A$ faceted sidewalls were etched into the n-type InP substrate. We obtained best wet etching results for 0.02% Br-methanol. This etchant provides low undercut of the mask and very sharp tips at the bottom of the grooves. To improve the optical quality of GaInAs/InP quantum wells grown after this etching without any buffer layer a second etching step was carried out in a $3H_2SO_4$:$1H_2O_2$:$1H_2O$ solution. Photo-luminescence (PL) studies on GaInAs wells proved reduced PL linewidth and increased intensity after the second etching.

Low pressure (80hPa) MOVPE growth was performed in a standard epitaxial system with horizontal reactor at a growth temperature of 620°C. To avoid rounding of the tip the GaInAs growth was started without any InP buffer layer. The GaInAs was embedded in a InP cap layer. Afterwards, the sample was cooled down under PH_3 stabilization and studied by cross sectional scanning electron microscopy (SEM) and low temperature PL (2K). The SiO_2 mask was not removed before epitaxy and therefore no growth was observed on (100) planes (Fig.1). The thickness of the GaInAs quantum well and the InP cap layer were varied. In Fig.2 a nominally 2.5nm GaInAs quantum well was grown into 1µm wide V-grooves. In PL three emission peaks were found. The peak at the highest energy is attributed to the (100) quantum well besides the masked area. The intense emission at 963meV is due to the quantum well on the $(111)_A$ sidewalls of the V-groove. From the quantum wire we find only weak PL emission at somewhat lower energy. This redshift of the wire emission can be explained by the migration of In and Ga to the bottom of the V-groove, resulting in an enhanced growth rate. Additionally, one part of the redshift arises from increased In content in the wire. This is consistent with the expectation that In is the more mobile adatom than Ga. For increased GaInAs layer thickness all PL-peaks shift to lower energies (Fig.3). A reduction of the wire period causes an increased PL intensity of the quantum wires and a decreased sidewall PL. This is clearly demonstrated in Fig.4 for a GaInAs wire array with a period of 450nm and stripe openings of 250nm.

The results are encouraging for further studies in the GaInAs/InP system. For improved GaInAs wire structures a DFB quantum wire laser seems to be possible.

Fig. 1: Cross sectional SEM picture of GaInAs (dark) /InP (bright) grown on SiO_2 masked V-groove substrates.

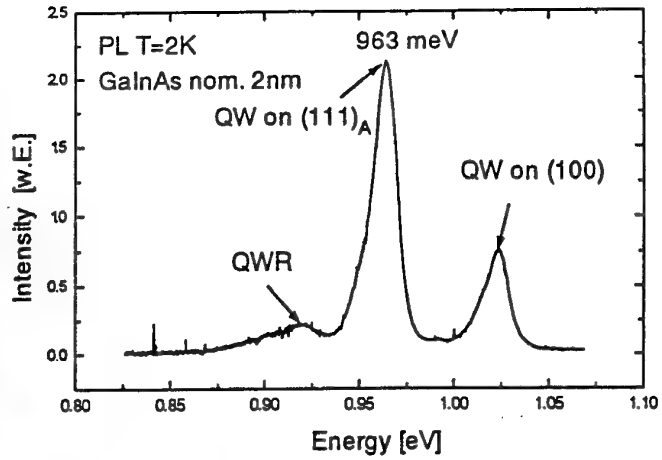

Fig.2: Low temperature photoluminescence of nominally 2nm thick GaInAs. QWR=quantumwire, QW=quantumwell

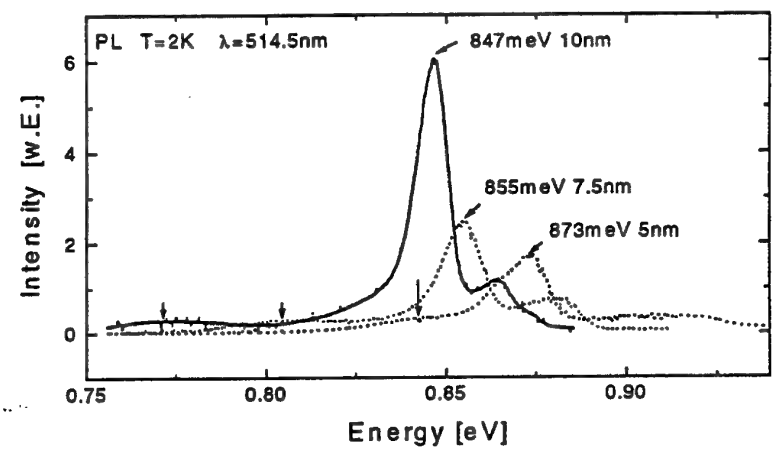

Fig.3: GaInAs/InP with three different growth times corresponding to a nominal layer thickness of 5nm, 7.5nm and 10nm.

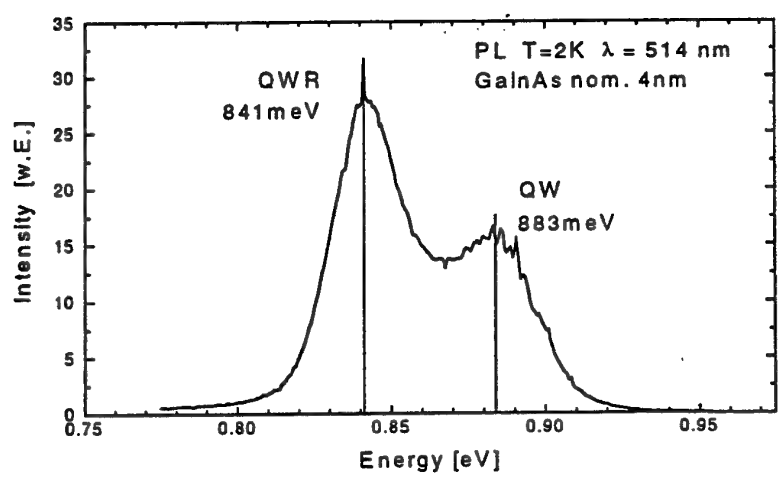

Fig.4: GaInAs/InP wire structure with a short period of 450nm.

Growth by selective area epitaxy on patterned substrates and characterization of GaInAs/InP nanostructures

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For the past few years, several methods of nanostructure fabrication have been investigated including growth on patterned substrates [1] or on substrates with non standard orientations [2]. We have shown using Chemical Beam Epitaxy that crescent shape GaInAs/GaAs quantum wires could be produced by selective area epitaxy [3,4]. Several series of GaInAs/InP structures have been grown using the same techniques on InP wafers and analyzed. We have studied samples where the structures were grown in 20 to 2 μm wide lines or in 1x1 μm squares patterned in SiO_2 masks deposited on InP. Growth conditions were adjusted to favor the occurrence of (111) facets of InP that eventually join to form a ridge or a pyramid on top of which GaInAs can be grown and capped with InP. The samples were studied by electron microscopy and by low temperature photoluminescence. Optical spectra are analyzed in light of high resolution field emission scanning electron micrographs of cleaved edges demonstrating In diffusion along (111) and (100). In particular, crescent GaInAs structures are clearly observed for narrow lines oriented along the [011] direction despite previously published results [5] that suggest that GaInAs does not grow on (111) InP facets.

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[2] *R. Nötzel, L. Däweritz, N.N. Ledentsov and K. Ploog, Surface Science, 267, 209 (1992)*
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Low Pressure OMCVD Growth of V-Shaped Quantum Wires

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Organometallic chemical vapor deposition (OMCVD) on non-planar substrates has been proven to be a promising method to form arrays of high quality one-dimensional quantum confined structures [1]. By performing growth at a total reactor pressure of 20mbar, we have been able to improve the interface quality and to reduce the lateral size of GaAs/AlGaAs quantum wires (QWRs) [2], with respect to atmospheric pressure (AP) growth, that has been traditionally used for this kind of structures. Low pressure growth is therefore promising for increasing the 2D quantum confinement in the QWRs and, thanks to the improved interface sharpness, for a better understanding of the self-ordering mechanism underlying QWR formation.

We have investigated the structure of GaAs/AlGaAs QWRs grown by low-pressure OMCVD on periodically corrugated V-grooved substrates, using transmission electron microscopy (TEM) and atomic force microscopy (AFM) in air. Although AFM does not have as high a lateral resolution as TEM, it can be used (in cross-sectional mode) to quantify local compositional variations of AlGaAs layers [3] and (in top-view mode) to visualize the topography of the surface of a QWR with subnanometer height resolution, up to a total length of 100 μm. This characterization is helpful for interpreting experiments, e. g., of carrier and exciton transport along the quantum wires.

Figure 1 is a TEM cross section of a QWR at the bottom of a V-groove. In contrast to AP growth, the upper boundary of the wire appears to be faceted, with a central (100) facet surrounded by two wider {311}A ones and, further out, by higher index (quasi-{111}A) sidewalls. The darker stripes at the center of the AlGaAs barriers are due to Ga accumulation at the bottom of the groove, and form a so-called vertical quantum well (VQW). The assignment of these darker-contrast AlGaAs areas to Ga accumulation is evidenced by cross-sectional AFM measurements of the oxide height on the AlGaAs [3, 4]. The origin of these VQW branches is clearly correlated with the faceting in the upper GaAs boundary of the QWR: the central branch stems from the (100) facet whereas the two lateral ones originate at the {311}A ones. The origins of the QWRs and of the VQW are therefore correlated, and result from preferential Ga segregation at these nanofacets.

In agreement with TEM cross sections, the AFM-height profile along a surface QWR shows the same kind of faceting. A {311}A facet can also be observed between the sidewalls of the groove and the (100) ridges between adjacent grooves. Figure 2 is a top-view AFM of a GaAs surface QWR, flattened across the V-groove, to evidence height variations along it in the different facets. In the (100) facets on the ridges and at the bottom of the groove, terraces separated by monolayer steps are observable. The {311}A facets show step bunching with a mean periodicity of ~50 nm and a height variation up to 5 nm, the latter being a function of facet width. In the quasi-{111}A sidewalls we observed only a random "long range" height variation (±10 nm) in the groove with a typical length of several hundred nm, due to inhomogeneities of the grating fabrication. The distribution of steps along and normal to the groove in the different facets could be responsible for the Ga segregation in the facets at its the bottom, and therefore for QWR and VQW formation.

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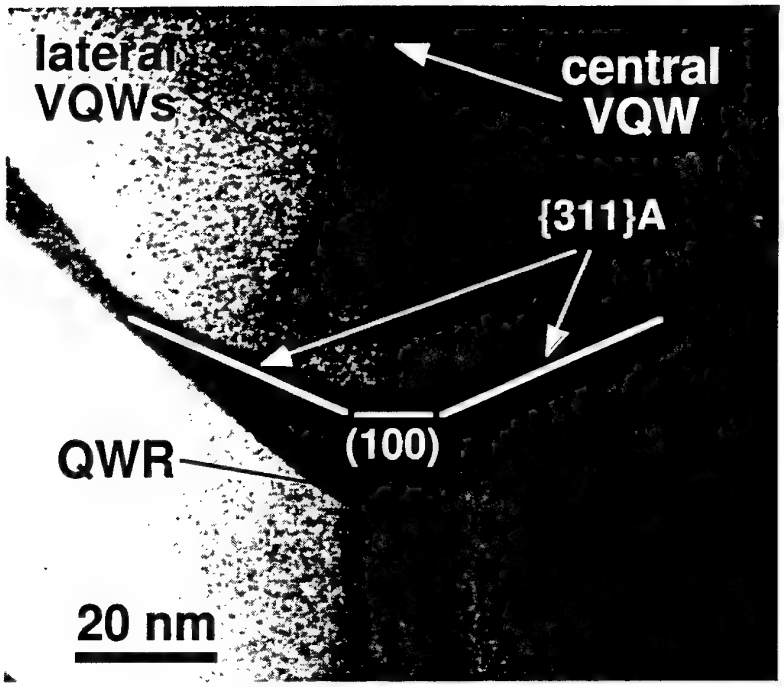

Figure 1: *TEM cross section of a QWR grown on a V-grooved substrate, showing the faceted nature of the wire profile, and the formation of a VQW at the bottom of the groove.*

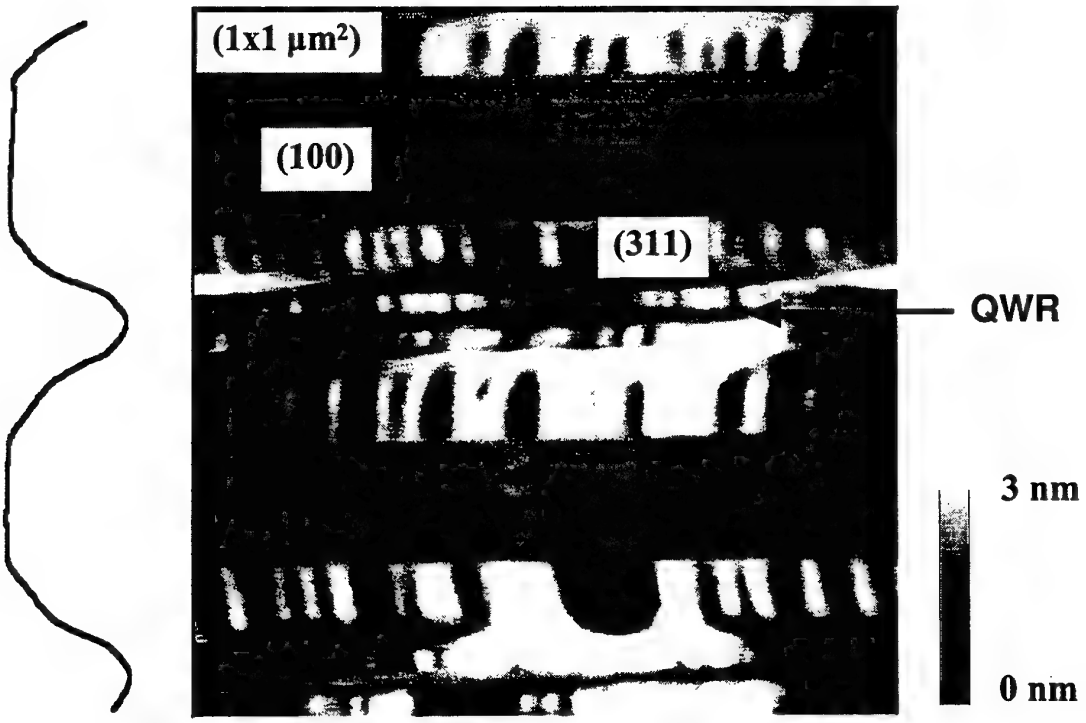

Figure 2: *AFM height profile of the GaAs surface of an AlGaAs/GaAs QWR heterostructure, deposited on a nonplanar substrate composed of 0.5μm-pitch grooves, showing the formation of monolayer steps on the (100) ridges, and of higher periodic corrugations on the {311}A facets.*

3D ARRAYS OF SELF-ORDERED QUANTUM DOTS FOR LASER APPLICATIONS: GROWTH AND PROPERTIES

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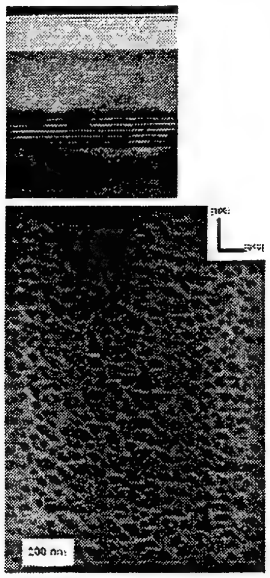
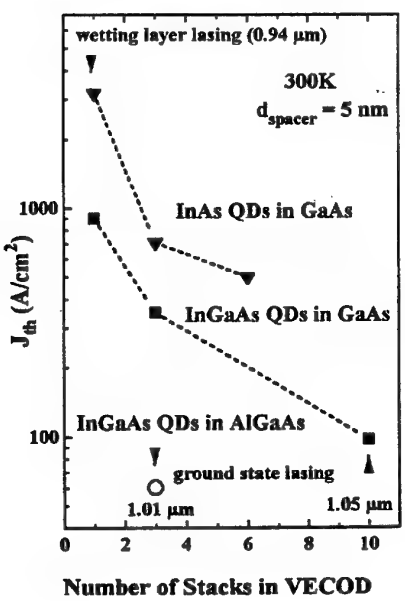
Spontaneous formation of three-dimensional (3D) coherent islands [1] on crystal surfaces which exhibit ordering in size, shape and in lateral arrangement brings a new challenge in physics and technology of semiconductor heterostructures.



Growth: The driving force for the formation of 3D islands in lattice-mismatched epitaxy is the *elastic strain relaxation*. Ordering in island shape and in their lateral arrangement [2] is mostly related to the anisotropy of the elastic moduli. Ordering in size relates to the total surface energy reduction, caused by the *relaxation of intrinsic surface stress* due to volume strain relaxation and due to appearance of edges. Short period alternate deposition of strained materials leads to a splitting of QDs and to formation of *vertically-coupled quantum dots (VECODs)*. Shape of QDs can be significantly modified during post-growth annealing. The InAs/GaAs dots are stable up to annealing times of 1 hr and temperatures of 700°C, even they increase the size and decrease the In composition.



Properties: If thermal evaporation of carriers from QDs is suppressed, InGaAs quantum dot (QD) lasers demonstrate low threshold current density J_{th} (60 A/cm^{-2}, 300K) operation and ultrahigh temperature stability of the threshold current with a characteristic temperature (T_0) of about 350-400K up to room temperature. High quality QD lasers can be grown by molecular beam epitaxy (see cross-section (upper) and plan-view (center) TEM images for MBE InGaAs-GaAs VECODs, number of stacks N=6) and by metal-organic chemical vapour deposition. Dependence of the J_{th} on N, on QD composition and on barrier composition for MBE-grown QD lasers is shown on the lower Figure.

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Intrinsic limitations and potential applications of InAs QBs obtained by self-organized MBE growth

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Strained InAs/GaAs QBs obtained by self-organized MBE growth have been extensively studied as a way to reach one of the frontiers of optoelectronics, a QB laser which would outperform QW lasers. The observation of a very narrow emission line (« kT) for isolated QBs and of fast carrier capture and relaxation processes for QB arrays have shown it is worth working hard to reduce the inhomogeneous line broadening due to QB size fluctuations within arrays.

Too major physical limitations to the efficient operation of lasers based on such QBs have not been enough considered until now. First, the PL line of isolated QBs broadens significant at high excitation levels, due to carrier-carrier interaction. This seems to place a lower limit (3-5 meV) on the width of the gain curve on an ideally homogeneous QB array. Secondly, thermoemission plays a crucial role in this system at near room temperature due to the weakness of the QB density of states compared to the DOS of "barrier" states. The buildup of a high density carrier population in the optical cavity (which increases optical losses) presumably explains why early QB lasers (see e.g. Kirsteader et al) lase on QB transitions at low T, but on barrier levels at 300K. We will show that the fabrication of coupled QBs is an efficient way to deepen QB levels, and to reduce both the impact of thermoemission processes and the inhomogeneous broadening of the emission of the QB array.

We will finally review some possible original applications of QB arrays, which can be undertaken at present, such as the fabrication of high efficiency QB LEDs on Si. On a more fundamental side, their application as probes of the photonic band structure of complex optical microcavities will also be presented.

Optical and Structural Studies of MOVPE Grown GaAs-AlGaAs v-groove Quantum Wires

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We will present the results of an optical study of MOVPE grown GaAs-AlGaAs v-groove quantum wires. This technique, which results from the different growth rates of GaAs and AlGaAs on the crystal surfaces produced when v-shaped grooves are etched into GaAs substrates, enables the fabrication of quantum wires with high optical quality. We will present new results demonstrating enhanced wire emission in electroluminescence (EL) compared to that observed in photoluminescence (PL). This observation in a p-i-n device is interpreted in terms of more efficient electron and hole capture when the two types of carrier are incident on the wire from different directions. Possible models for this behaviour will be considered. We also observe enhanced PL emission from modulation doped wires. This result allows the study of the PL over a wide range of incident laser powers. For very low laser powers the broad wire PL, observed for high incident powers, splits into a series of sharp features which we attribute as being due to wire size fluctuations or potential fluctuations produced by the remote donor ions. EL spectra recorded as a function of current in a p-i-n device show clear evidence for band filling effects. Recombination involving transitions between the electron and hole ground states and at least two excited state transitions are observed. Similar effects are observed in the PL spectra of quantum wires. These results allow the separation of the 1D subbands to be determined. A maximum value of ≈30meV between the ground and first excited state transition has been obtained. In addition to emission from the wire, the optical spectra of the structures show emission from quantum wells of different thicknesses formed on the {111}A side walls of the grooves and the (001) regions between the grooves. Emission is also observed from a Ga rich vertical AlGaAs quantum well. The origin of the various emission lines is determined using spatially resolved cathodoluminescence and PL measurements of samples from which different amounts of material has been removed by etching.

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STRUCTURAL AND OPTICAL CHARACTERIZATION OF SELF ORGANIZED InAs-GaAs QUANTUM DOTS GROWN ON HIGH INDEX SURFACES

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We report the results on self-organized InAs QDs grown on novel index GaAs surfaces by Molecular Beam Epitaxy. The InAs QDs were formed on (100), (111)B, (311)A and (311)B GaAs planes using a coverage of InAs of 1.8 Mls. STM morphological characterization has been performed showing uniformity of QD coverage for all the samples with the exception of (111)B which exhibits a surface characterized by very large islands and where STM pictures give no evidence of Qds formation. All the samples show photoluminescence (PL) of evident QD origin with broad (about 60 meV) peaks in the range 1.15 to 1.35 eV.

The PL intensity of the (111)B sample is weaker (two orders of magnitude) than that of the other samples. A good efficiency is observed on (100), (311)A and (311)B surfaces, with no significant quenching of PL up to the temperature of 77 K. These results suggest that the high index substrates are promising candidates for production of high quality self-aggregated QD materials for application to photonics. Further investigations are on the way in order to clarify the substrate orientation depedence of morphological and optical properties of InAs QDs.

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SPATIALLY RESOLVED OPTICAL SPECTROSCOPY OF GaAs ISLANDS ON InAs (111)

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The growth of heterostructures with mismatched materials offers interesting design possibilities. For example, the built-in strain can be used to generate piezoelectric effects in epitaxial layers grown on high index surfaces. The lattice mismatch can also be a driving force for self organized growth : high density arrays of InAs quantum dots were obtained on (001) oriented GaAs substrates.[1-2] The study we present here is related to islanding on (111) oriented substrates.

GaAs layers were grown by MOVPE on (111) oriented InAs. The large lattice mismatch leads to three-dimensional island formation. The strain relaxation in the structures is measured by Raman Spectroscopy and photoluminescence. In this paper we focus on spatially resolved measurements (using a micro Raman set) performed on µm-sized GaAs islands with pyramidal shapes (three-fold axis). The topography is performed on a single isolated pyramid [Figs. 1 and 2]. The existence of the remaining GaAs film in between the islands is evidenced. The local strains are deduced from the optical phonons frequency shifts [Fig. 3(a)]. The topography evidences the strain profile (around and across the pyramid) resulting from the three dimensional surface structuration. High residual tensile strains are found [Fig. 3(c)]. The strain profile deduced from spatially resolved photoluminescence [Fig. 3(b)] is in good agreement with the Raman data. Furthermore, isolating a single pyramid allows us to determine precisely the Raman selection rules (dependence of LO and TO intensities on the polarization configuration and position). The latter are correlated to the different surface orientations [(111) GaAs film and pyramid facets close to (110)].[3] Symmetries, anisotropies and structural disorder effects are discussed.

The detailed study of single island can now be used as a precious guide for investigating islands with nm sizes by Raman spectroscopy. For example, by choosing accurate polarization configurations, the wetting layer and quantum dots contribution to the Raman spectra can now be identified and separated. Furthermore, as illustrated by the present work, micro-Raman spectroscopy emerges as promising characterisation technique for devices and structures used in microelectronics (determination of stress[4] , local temperatures, ...).

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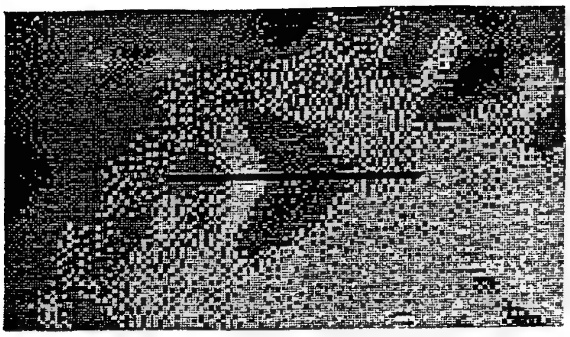

Fig. 1. GaAs pyramid : optical microscope image (x100 objective). --- 1μm

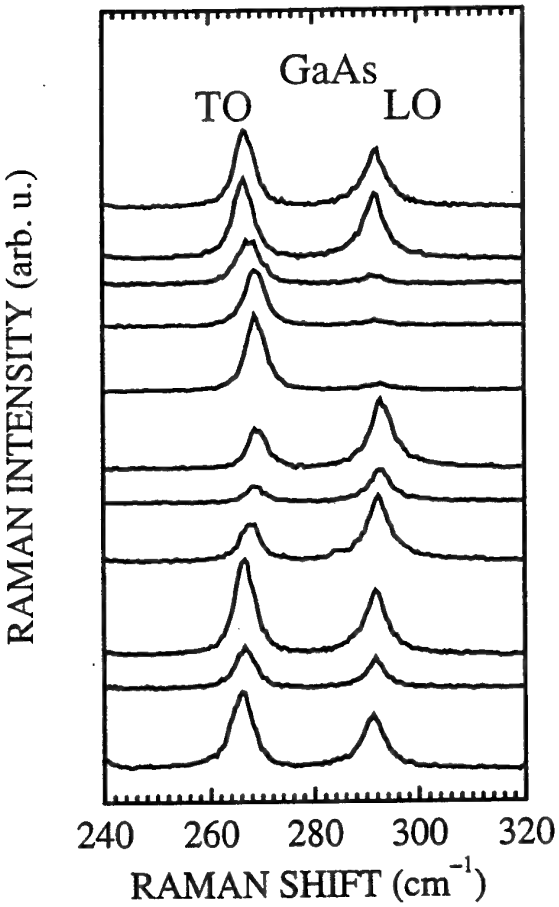

Fig. 2. Raman spectra. Pyramid topography according to the scanning line indicated in Fig. 1. (parallel polarization configuration)

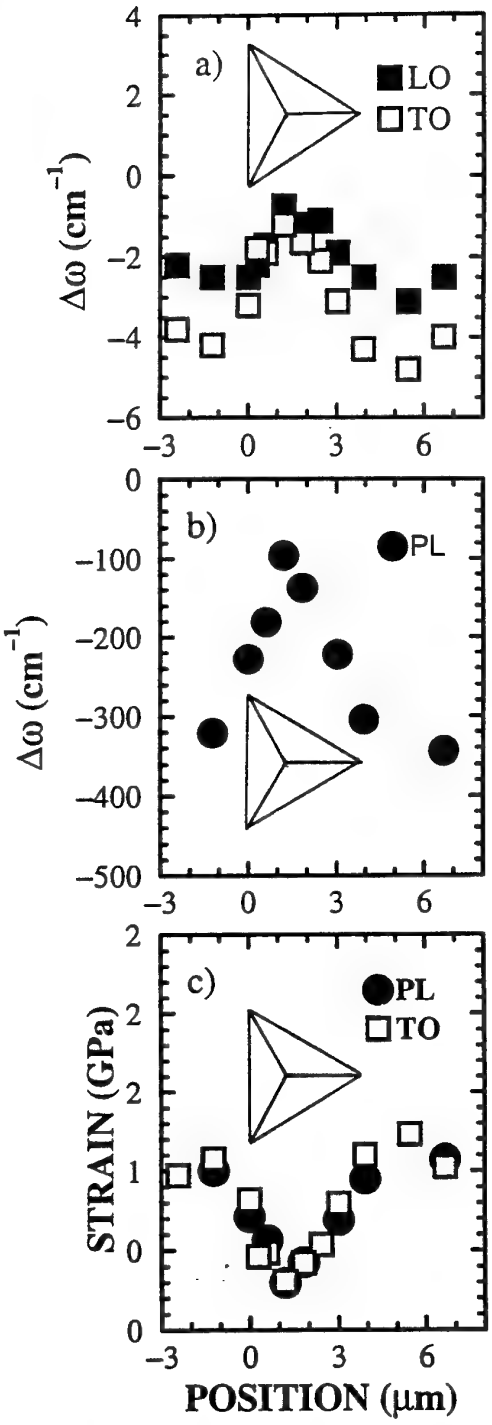

Fig. 3. Frequency shifts vs position : (a) Optical phonons and (b) Photoluminescence (PL). (c) Strain deduced from Raman and PL data. The position is given with respect to the sketch of the pyramid.

Novel piezoelectric-barrier heterostructure for all-optical light modulation

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We present early experimental results demonstrating a novel all-optical piezoelectric-barrier quantum well (QW) modulator. The device is designed such that an incident control laser beam with a moderate optical power of the order of 10W/cm^2 strongly modulates the ground state QW resonance of the heterostructure. Essential to this design is the fact that in strained semiconductor heterostructures grown along a polar axis (in our case (211)), the lattice-mismatch induced strain generates a large piezoelectric field along the growth axis [1].

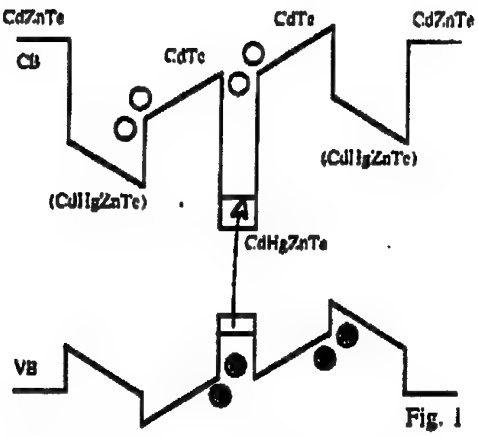
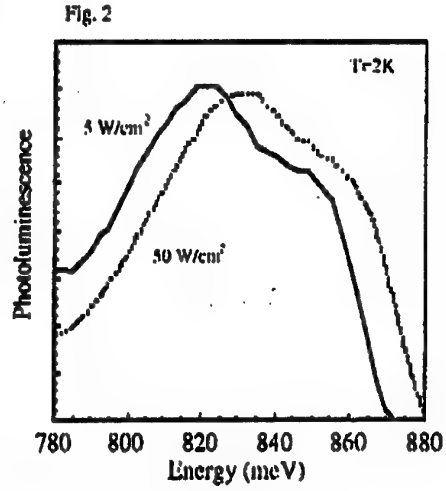


Fig. 1

In Fig. 1, we show the band diagram of one period of the heterostructure grown coherently on a (211) $Cd_{0.96}Zn_{0.04}Te$ substrate. The period consists of three QWs. The outer QWs consist of 400Å of $Cd_{0.67}Hg_{0.25}Zn_{0.08}Te$, and are separated from the middle QW (whose resonance is the ground state of the heterostructure and the one to be all-optically modulated) by 400Å-thick CdTe barriers. The middle QW consists of 200Å of $Cd_{0.61}Hg_{0.37}Zn_{0.02}Te$ and its composition is designed such that it is lattice matched with the substrate and its bandgap is around 1.5μm. The CdTe is under compression whereas the outer QWs under dilation. The strain induced piezoelectric field in these layers is around 50kV/cm.

The principle of operation of this device, which can be easily transposed to other strained heterostructure systems and wavelengths of operation [2], is the following: a control optical beam photogenerates electrons and holes in the piezoelectric barrier layers. There, the piezoelectric field separates the carriers on either side. The collected carriers in the middle QW deplete radiatively, and the end result of the optical excitation is an accumulation of electron and hole populations in the outer QWs. This creates an electric field which shifts the excitonic resonance of the middle QW through the Quantum Confined Stark Effect (QCSE). In Fig.2, we show photoluminescence (PL) spectra from the middle QW as a function of power density at T=2K. The control beam here consists of Argon blue laser lines. We observe a clear blueshift of about 10 meV as we increase the power density by a factor of 10. The fact that we observe blueshift, as opposed to redshift according to QCSE, indicates a pre-existing electric field in the structure at low temperatures. This is confirmed by the fact that at higher temperatures (T=130K) we observe a redshift of the PL line for the same power increase. Finally we note that the modulation effect disappears for this structure above 200K, most probably due to important thermionic emission which allows the collected charges in the outer QWs to find each other and recombine. This should be easily remedied, by replacing the CdTe barrier layers by a larger bandgap material such as CdMgTe.

Fig. 2



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Growth of (111) B growth multilayers for optoelectronic devices

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Growth of GaAs and (Ga,Al)As (111)B layers on GaAs substrates has been investigated in the 680 - 520°C temperature range suited for growth of (Ga,Al)-GaAs and (Ga,Al)As-(Ga,In)As optoelectronic devices. Comparison of growth conditions for nominal and vicinal orientations will be discussed on the basis of atomic force microscopy observations.

First results will be presented on growth of Bragg reflectors based on GaAs and $Ga_{1-x}Al_xAs$ (x=1 - 0.5) multilayers and GaAs-(Ga,Al)As and (Ga,In)As-GaAs multiquantum wells, key elements of vertical surface optoelectronic devices, such as surface emitting lasers or Fabry-Perot resonators.

1.3μm Lasers on GaAs(111)B Employing Ordered $(InAs)_1(GaAs)_1$ Quantum Wells for High Frequency Response Applications

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Abstract

The ever increasing use of fiber optics has motivated device designers to strive for high speed sources to drive these fiber-based networks networks. For such applications, 1.3μm and 1.55μm are the wavelengths of interest, being the minimum in dispersion and absorption in silica fiber, respectively. Because several of the various multiplexing schemes require large bandwidths, directly modulated lasers have been made on InP at these wavelengths. Modulation bandwidths in the low to mid 20 GHz[1] currently represent the state of the art in this material system. Record 3dB bandwidths up to 40 GHz[2], however, have been achieved with InGaAs/GaAs(001) lasers, but the wavelengths of interest are normally unattainable in this material system.

In order to reach these longer wavelengths with GaAs based devices, we propose a novel structure incorporating a monolayer superlattice, or ordered structure, of $(InAs)_1(GaAs)_1$ in the quantum well of a laser on GaAs(111)B. The period of this ordered structure is doubled in real space, and the Brillouin zone is halved in reciprocal space as compared with the random alloy. Upon zone folding and level repulsion at the band edge, the bandgap of the monolayer superlattice is narrowed with respect to the random alloy as has been experimentally observed with $(GaP)_1(InP)_1$. This narrowing has been calculated for both (001) and (111) orientations[3], and has been found to be have a much greater effect on the (111) surface. The calculated conduction band to heavy hole transition energy versus degree of order for such a quantum well with GaAs barriers is shown in Fig. [1]. In the random alloy case, no advantage is gained by moving to the (111) orientation despite the fact that Matthews-Blakeslee's critical thickness is approximately doubled as seen in Fig. [2]. The decrease in the quantum confinement energy due to the wider well is mostly offset by the increased hydrostatic strain contribution to the Hamiltonian. The benefit of moving to this higher index surface, however, is readily apparent as the degree of ordering is increased.

As seen in Fig. [1], wavelengths up to and beyond 1.3μm are theoretically possible on GaAs(111)B. With the first reported cw operation of InGaAs/GaAs(111)B quantum well lasers[4], these ordered structures are not beyond the current level of technology. Additionally, the recent report that the piezoelectric field is only partially screened above threshold[5] should only aid in achieving longer wavelengths in this material system. Finally, we discuss the advantages of moving to the (111) orientation, including lower threshold current densities and smaller linewidth enhancement factors.

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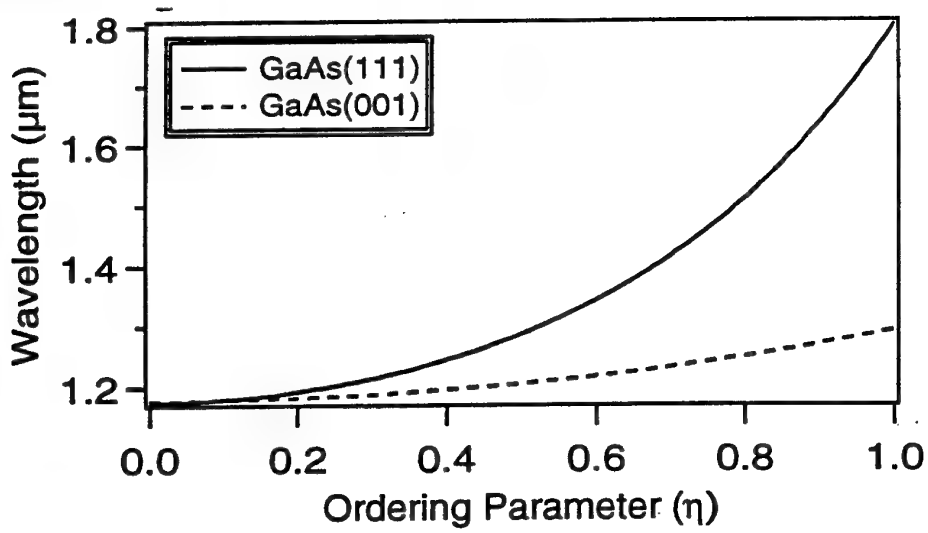

Fig. [1] Calculated emission wavelength for an $In_{0.5}Ga_{0.5}As$ quantum well at the Mathews-Blakeslee critical thickness for two different GaAs crystal orientations with increasing degree of ordering. The random alloy is given at 0 and the perfect monolayer superlattice is given at 1.

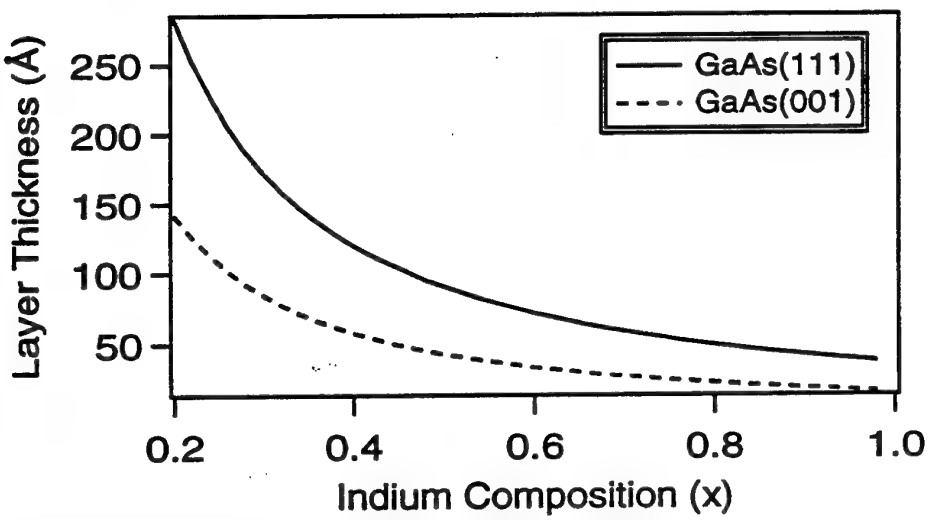

Fig. [2] Mathews-Blakeslee critical thickness for $In_xGa_{1-x}As$ quantum wells on two different GaAs crystal orientations.

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Strained Layer Piezoelectric Semiconductor Devices

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III-V quantum wells grown pseudomorphically strained on axes other than <100> incorporate piezoelectric fields which modify their electronic structure and optical properties. The principal effects are:

- an intrinsic Stark shift to the red resulting from the built-in field,
- modified electric fields in the unstrained barriers, maintaining the external potential,
- a reduction in oscillator strength for the fundamental quantum confined interband transition resulting from the separation of the electron and hole ground states,
- the observation of interband transitions, forbidden in 'square' wells, resulting from the reduced symmetry,
- a Stark shift to the blue under external bias applied to compensate the internal field,
- screening of the internal field by optically excited carriers.

Some of these effects have been proposed, and a few demonstrated to offer improvements to the performance of some optoelectronic devices, including electrooptic modulators, FETs, optical switches and blue-shifting SEEDs. In this talk we shall discuss these improvements, together with our own observations on piezoelectric MODFETs, all-optical S-SEEDs and integrated laser/waveguide modulators. The talk will concentrate mainly on the work of the Sheffield Semiconductor Group in the strained InGaAs/GaAs/AlGaAs and InGaAs/InP/InAlAs systems grown by MBE on (111)B.

(111) oriented substrates for optoelectronic device applications

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The interest for this particular substrate orientation is stimulated by its specific properties. These include internal piezoelectric field, favorable configuration of the valence band for laser emission and different polarization selection rules for nonlinear optics. A large number of devices utilizing this non-conventional substrate orientation have been fabricated worldwide including quantum well lasers, pseudomorphic high electron mobility transistors, double barrier resonant tunneling diodes and blue-shifting light modulators.

In addition, the limit Indium incorporation before interface degradation in a GaInAs quantum well can be increased and the non-radiative recombinations in AlGaAs much reduced when compared to the (100) case. This last point is critical for applications to minority carrier devices and to quantum well lasers in particular. We present results of (111)B InGaAs/GaAs/AlGaAs GRINSCH quantum well lasers that show nearly unity internal quantum efficiency even for cases where carrier concentrations at threshold are high.

Other interesting properties can arise from the possibility to control the atomic step distribution on a (111)B surface by the growth conditions. The very different growth behaviour for substrates misoriented towards (2-1-1) or (-211) originates from the instability of the terrace edges descending towards the (-211) direction. They tend to decompose into sawtooth-like edges where all steps are equivalent to stable steps descending towards (2-1-1). We show that the conditions in the (As pressure - substrate temperature) phase space to obtain high-quality material are complementary for the two opposite misorientations. Nucleation of additional steps has to be avoided when dealing with one single type of stable steps whereas it is needed when two types of stable steps are already present on the surface. We also show that by varying the conditions, it is possible to produce regular arrays of monosteps or macrosteps.

POSTERS

POSTER SESSION

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Poster 17	G. Grenet, M. Gendry, Y. Robach, P. Krapf, L. Porte, G. Hollinger. Role of surface energy of (001) and (11n) facets on the 2D to 3D growth mode transition of strained $In_xGa_{1-x}As$ layers on InP(001).
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LEED and photoemission study of MBE-prepared GaAs(112), (113), and (114) surfaces

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High-index surfaces of GaAs and GaAlAs have attracted interest in connection with the preparation of low-dimensional quantum structures [1]. We have developed a compact transportable MBE-setup for preparation of GaAs surfaces.

We study our surfaces with spot-profile analysis LEED, Augerelectron spectroscopy, and also photoelectron spectroscopy from the valence band and shallow core levels. Recently, we moved the MBE-setup to BESSY to study surface core level shifts from Ga and As 3d levels of in-situ prepared GaAs(001), (112), and (113) surfaces.

For our samples we used wafers with a size of about 6x12 mm2 which were cleaned by sputtering and annealing in UHV before about 25 layers were grown in about 2 cycles. The oven temperatures and equivalent beam pressure were adjusted accordingly.

For GaAs(001) we observed most of the known superstructures. We found GaAs(113)A reconstructed exhibiting a 8x1 unit cell in agreement with the RHEED analysis of Wassermeier et al. [2]. The GaAs(112) is found to be faceted which may be largely due to (110) faces as concluded from the surface core level shifts. The studies are continued with (114) surface for which we expect that the order of the surface depends on the As coverage [3].

We correlate the preparation conditions with the LEED structures and long-range order, the chemical composition (As/Ga composition ratio) and the electronic properties (ionization threshold, Fermi level position) for the stable structures on the GaAs(113)A- and B-surfaces. Special emphasis is given to the existence range of the recently observed GaAs(113)A-(8x1) structure [1,2]. Its existence is confirmed by LEED. Under the same preparation conditions the (1-1-3-)B surface is faceted.

We will compare the surface core level shifts. Whereas the (001) surface exhibits basically only one shifted component, two components are observed for GaAs(113)A surface which correlates with the given structure model [2].

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Growth studies of self-organised InAs dots on (100), (311) and patterned GaAs substrates.

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Investigating the growth of InAs and InGaAs quantum dots (QDs) on GaAs is motivated, on one hand, by the desire to understand the fundamental processes of nucleation and growth of thin pseudomorphic layers(1), and on the other hand, by the expectation of unique properties of QDs. These include the δ-function density of states which can lead to novel and/or strongly improved properties of photonic and electronic devices, such as lasers(2).

It has been shown that in-situ epitaxial growth of coherently strained islands allows the attainment of a high level of quantum confinement(3-6). The generation of such three-dimensional (3D) islands is considered to result from a morphology evolution of the 2D layer after the growth of 1-2 monolayers (ML). Either elastic relaxation of the strain in heterostructures, i.e. a local minimum of energy, or the kinetics of strain induced surface roughness have been assumed to be responsible for self-organised formation of nm-size 3D islands. However, a conclusive picture for the 2D-3D morphology transformation has not previously been established.

Most previous studies have investigated the relationship between the growth conditions and the size and concentration of the dots on flat (100) GaAs surfaces. However, the lack of spatial control of InAs dots with this method tends to place constraints on possible applications of quantum dots in electronic and optical devices.

In this study, we investigate the molecular beam epitaxy (MBE) growth of self-organised InAs quantum dots on (100), (311) and patterned GaAs substrates. The morphology of the InAs films is studied using an in-situ ultra-high vacuum scanning tunneling microscope (STM) attached to the MBE system.

We have grown InAs of different thicknesses from 0.6 ML to 4 ML on (100) GaAs substrates.The STM images, shown in figure 1, reveal the presence of 70 Å×200 Å dots for 1.2 ML (figure 1.c) and above (figure 1.a and 1.b). At 0.6 ML (figure 1.d), the growth mode is two-dimensional with very elongated islands along the $[1\bar{1}0]$ direction. For 1.2 ML, the dot density is 6.8×10^{8} cm^{-2} and they have nucleated predominantly on terrace edges (figure 1.c). The dot density increases up to 2.2×10^{9} cm^{-2} for 2.1 ML. For 4 ML, the density of dots is 2.1×10^{9} cm^{-2} although very big islands have also formed beside the dots. The high concentration of small dots around these islands (figure 1.a) could indicate that they are due to the coalescence of a several small dots.

To achieve the best homogeneity in dot size, we will study the appearance of the dots and the InAs film morphology as a function of coverage, growth conditions and GaAs surface orientation. The step density at the surface of the underlying GaAs surface should affect the dot nucleation as they grow preferentially on terrace edges. The surface kinetics are expected to have an influence on the beginning of the 2D-3D growth mode transition. The GaAs surface orientation will also affect dot nucleation as it changes the surface energy and the adatoms mobility during growth. Finally, we will apply our results to patterned substrates, in order to control the organisation of the dots.

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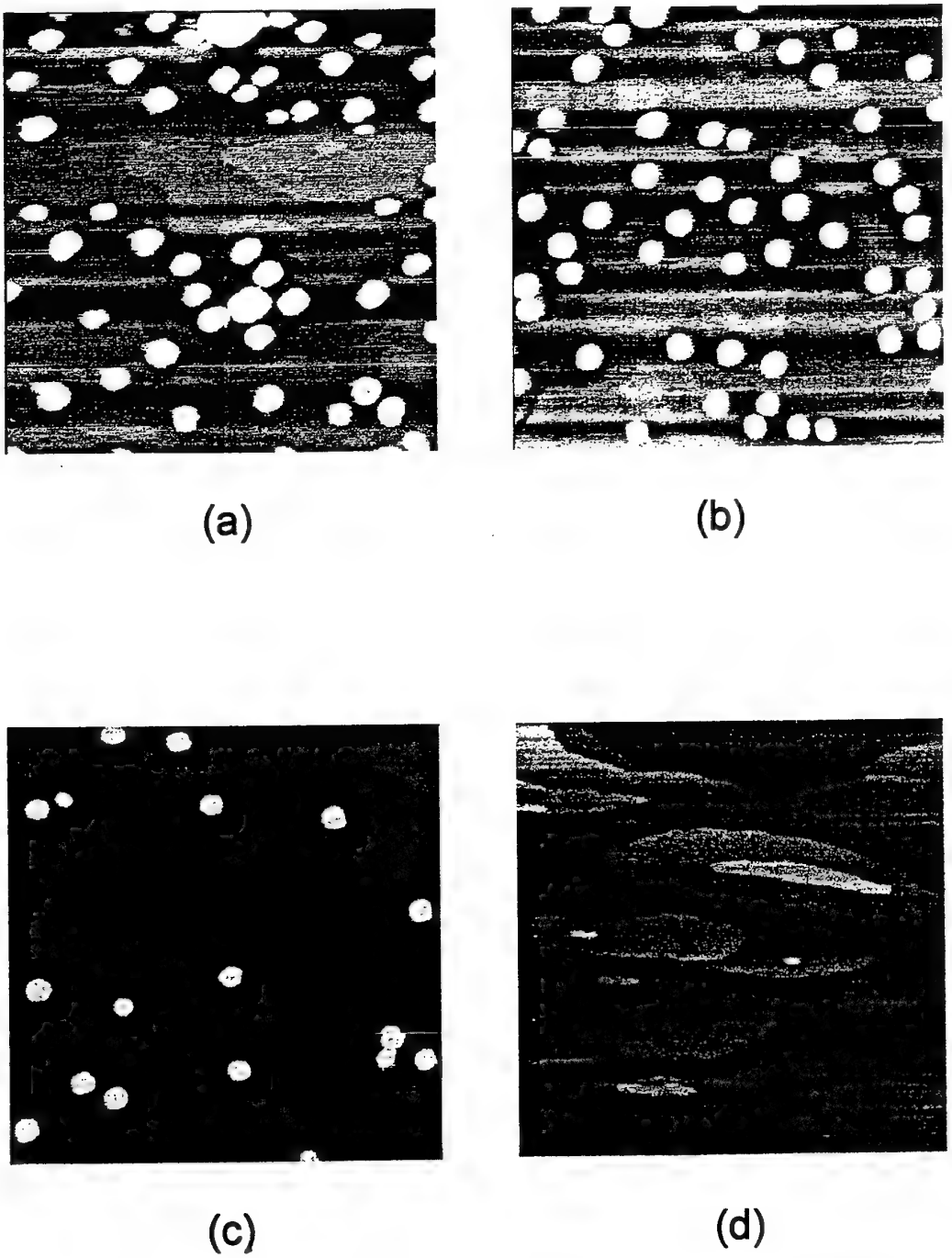
figure 1. 500 nm×500 nm STM images showing the surface morphology and dot density for different InAs coverage: a) 4 ML, b) 2.1 ML, c) 1.2 ML and d) 0.6 ML.



Incorporation behaviour of carbon and silicon on (100) and {111} surfaces during growth of GaAs/GaAs and $Ga_{0.47}In_{0.53}As$/InP by molecular beam epitaxy

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In general, group IV dopants such as *silicon (Si)* and *carbon (C)* show amphoteric incorporation behaviour and can either act as a donor or as an acceptor in III-V semiconductors. On {111} surfaces the incorporation behaviour of these dopants and of group III elements (e.g. Ga/In) can be different from (100) surfaces depending on growth parameters. Different incorporation mechanisms of group III and IV elements on different surface orientations can be systematically utilized for novel device applications during the growth on *patterned* substrates where both (100) and {111} surfaces are present. In the growth on patterned substrates the incorporation behaviour on the local (100) and {111} planes can be affected by interfacet diffusion. Hence we started at first a systematic study of dopant and group III element incorporation on (100) and {111} large area surfaces. The results form a mandatory basis to understand the incorporation mechanisms on patterned substrates.

We have grown *silicon*- and *carbon*-doped layers of GaAs and $Ga_{0.47}In_{0.53}As$ on GaAs and InP, respectively, with surface orientations (100), (111)A and (111)B. For clear comparison the layers were grown on the three substrate types in a single growth run. *Carbon*-doped films were obtained using carbon tetrabromide (CBr_4) injected into the growth chamber via a simple setup. The electrical properties of the samples were determined by Hall and van der Pauw measurements. The ratio of the group III elements in the layer was measured by X-ray diffraction and/or room temperature (RT) photoluminescence (PL).

In solid source molecular beam epitaxy (MBE) on (100) surfaces *silicon* is predominantly incorporated on group III lattice sites leading to n-type conduction for the growth of GaAs on GaAs as well as for $Ga_{0.47}In_{0.53}As$ on InP applying standard growth parameters (see Table 1). On the other hand *carbon* is mainly incorporated on group V sites therefore acting as an acceptor.

The conduction type of *silicon*-doped GaAs changes from n on (100) to p on (111)A surfaces already under standard growth conditions (see Table 1). In contrast the conduction type of $Ga_{0.47}In_{0.53}As$ layers doped with *silicon* remain n-type on {111} surfaces whereas the free carrier concentrations are enhanced by a factor of 2-4 compared to the (100) surface.

Using CBr_4 instead of silicon in the growth of doped GaAs *carbon* is solely incorporated as an acceptor on both (111)A and (100) surfaces, moreover, even resulting in similar free hole concentrations (Table 1). All *carbon*-doped $Ga_{0.47}In_{0.53}As$ layers grown on (100) and {111} InP surfaces show p-type conduction. The free hole concentrations on overgrown (111)A surfaces are independent of the growth temperature and only limited by the mass transport from the dopant source. In the growth of *carbon*-doped $Ga_{0.47}In_{0.53}As$ on (111)B and (100) planes the hole concentration can be additionally controlled by the growth temperature. Lowering the growth temperature from 515°C to 450°C the hole concentration increases by a factor of 20-40. At a growth temperature of 450°C the free hole concentration on both (111)B and (100) overgrown surfaces is very close to the free hole concentration on the (111)A surface.

For the growth of $Ga_{0.47}In_{0.53}As$ below the Indium desorption regime ($T_{growth} < 530°C$) the Ga/In ratio in GaInAs layers grown on {111} and (100) surfaces is identical which has been verified by RT-PL. Hence the sticking coefficients of the group III elements Ga and In are

independent of the surface orientations (100) and {111} when applying standard growth parameters.

	(100)	(111)A	(111)B	T_{growth}, V/III
GaAs:Si	n $6.3 \cdot 10^{17}$ cm^{-3}	p $7.6 \cdot 10^{17}$ cm^{-3}	n*)	585°C 30
GaAs:C	p $1.7 \cdot 10^{18}$ cm^{-3}	p $1.5 \cdot 10^{18}$ cm^{-3}	p*)	585°C 30
GaInAs:Si	n $7.8 \cdot 10^{17}$ cm^{-3}	n $2.7 \cdot 10^{18}$ cm^{-3}	n $2.2 \cdot 10^{18}$ cm^{-3}	515°C 47
GaInAs:C	p $2.8 \cdot 10^{17}$ cm^{-3}	p $1.4 \cdot 10^{19}$ cm^{-3}	p $5.9 \cdot 10^{17}$ cm^{-3}	515°C 49
GaInAs:C	p $1.1 \cdot 10^{19}$ cm^{-3}	p $1.5 \cdot 10^{19}$ cm^{-3}	p $1.2 \cdot 10^{19}$ cm^{-3}	450°C 42

Table 1: Conduction type and free carrier concentration of GaAs and $Ga_{0.47}In_{0.53}As$ layers doped with silicon (Si) or carbon (C) and grown on substrates with orientations (100), (111)A, (111)B.
*) at present only n-type substrates are available.

Spatially resolved Raman investigation of Si-doped GaAs layers on patterned GaAs(100) substrates grown by MBE

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In the growth of epitaxial layers on patterned surfaces the material properties are affected by the different local growth mechanisms, surface kinetics, the interfacet diffusion and the desorption of the growth species. Hence, the potential of a lateral material confinement for novel device applications is accessible. Here, among other issues the dopant incorporation at the higher index planes in localized structures is still unclear. It is well known that in GaAs-MBE on large area surfaces Si shows amphoteric behavior. In layers grown on GaAs(100) and (111)B substrates it acts as a donor and in layers on (111)A substrates as an acceptor or as a donor depending on the growth conditions.

In this study we investigate the Si incorporation in GaAs layers re-grown on patterned GaAs(100) surfaces exhibiting (100) as well as high index (111)A and (111)B facets. SEM inspection yields that the grown layer tracks closely the pregrown local surface structure. To characterize these structures we used Micro-Raman spectroscopy, which is an excellent tool to determine laterally resolved the type and density of free charge carriers in the grown layer on the different index facets.

In doped polar semiconductors the LO-phonon mode couples with the plasmon mode of the free carriers resulting in two coupled plasmon-LO-phonon (PLP) modes L+ and L-. In n-type GaAs both PLP-modes can be detected. For $n \geq 1e18$ cm^{-3} the frequency of the L+ mode is above the LO-frequency and clearly depends on the free electron concentration. In p-type GaAs only one line arising from the PLP-modes appears in the Raman spectrum. Whereas its frequency only slightly shifts from the LO- to the TO-phonon position with increasing hole concentration, its linewidth clearly depends on the free-hole concentration and is used to determine it for $p \geq 1e18$ cm^{-3}. In consequence, from this different behavior of the PLP-modes, n- and p-type doping can be distinguished.

Our Raman measurments show that the grown layer is p-type on the (111)A facets at high substrate temperatures and low As/Ga flux ratio. At low substrate temperature and high flux ratio the layer on the (111)A facets switches to n-type. This behavior is identical for growth on large area (111)A substrates. In the GaAs on the (100)- and (111)B-facets Si is primarily incorporated as a donor not depending on the growth condition. The density of free electrons is comparable for the material on the localized (100) and (111)B facets with respect to the material on an unpatterned GaAs(100) surface. Spatially resolved PL-measurements performed on these samples and Hall measurements performed on layers grown on unpatterned substrates of different orientations confirm these findings. Thus, these spatially resolved Raman measurements prove that lateral p-n junctions can be fabricated in a single growth run during the overgrowth on structured surfaces, enabling a carrier confinement.

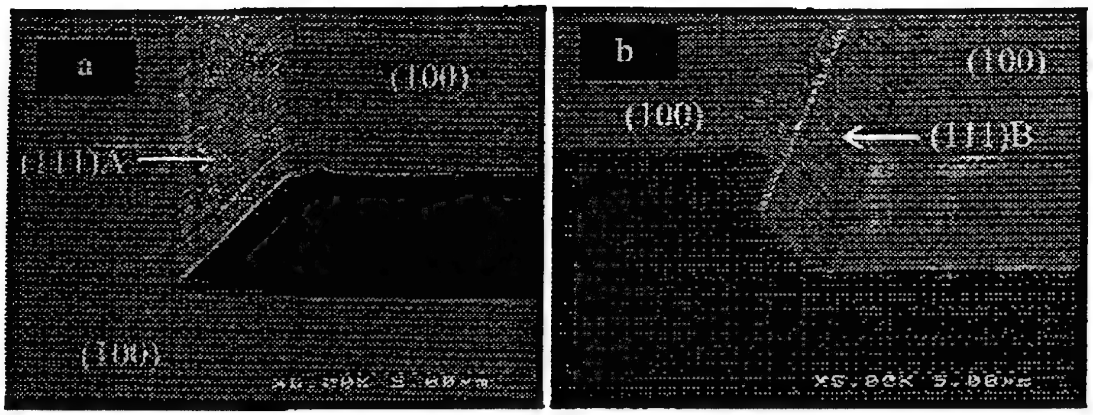

Fig. 1: SEM micrographs showing the surface of a grown layer at: (a) a (111)A facet. (b) a (111)B facet.

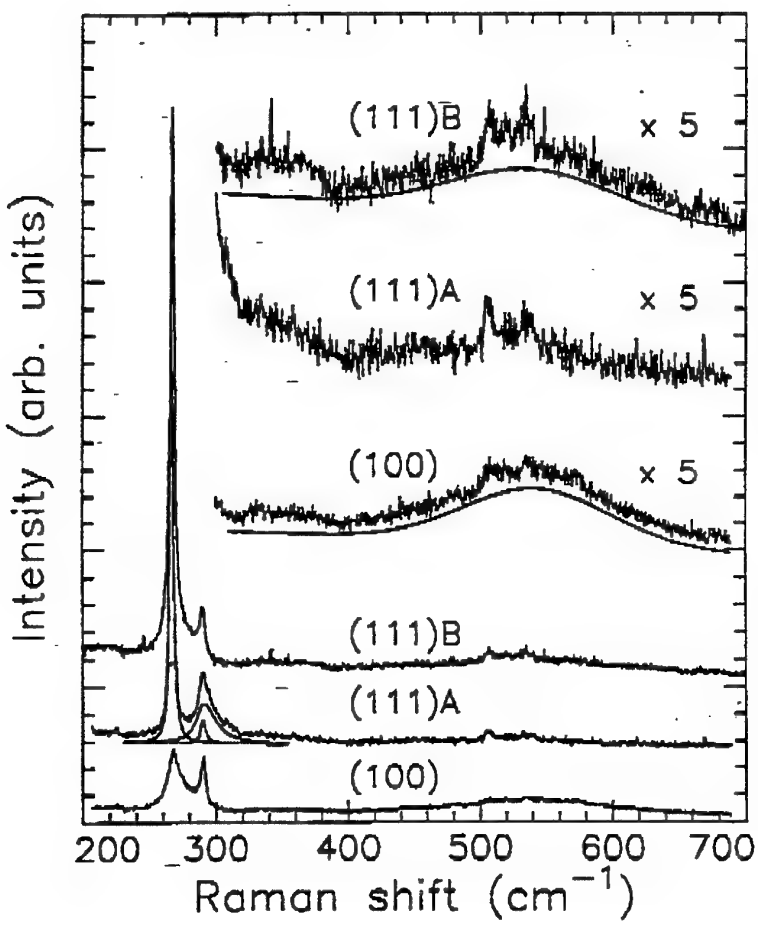

Fig. 2: Spatially resolved Raman spectra measured at a (111)B-,a (111)A-,and a (100)-facet, proving n-, p-, and n-type doping, respectively.

Growth of Strained GaInAsP Materials on (111)B Oriented InP Substrates by Atmospheric Pressure MOVPE.

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III-V semiconductors grown on non-(001) oriented substrates have many potential benefits. If strained materials are grown on a polar orientation, such as (111), novel non-linear optical effects have been predicted, due to the internal piezoelectric fields created[1]. This built-in strain generated field may be reduced by application of an external electric field or screened by photoexcited carriers. A blue shift of the band edge is observed in both cases[2,3].

In order that these novel effects can be incorporated into devices suitable for telecommunications systems operating at 1.3 and 1.55μm, we have investigated the growth of strained GaInAsP alloys on InP substrates oriented in the (111)B direction.

A horizontal flow, atmospheric pressure metal organic vapour phase epitaxy (MOVPE) reactor was used for the growths. Sources were arsine, phosphine, trimethylindium and trimethylgallium. The substrate orientation was miscut 2° from (111)B towards the $(0\ \bar{1}\ \bar{1})$ direction in order to achieve good surface morphology[3]. In addition every growth run included some (001) material as a control.

Growth of specular InP was achieved by increasing the growth temperature by 50°C from our usual (001) growth conditions. The sulphur and zinc doping characteristics of InP grown in the (111)B direction has also been investigated.

In order to achieve specular morphology on the strained GaInAsP alloys, it was necessary to use a fast growth rate of about 6.5μm/hr and maintain a fairly low V/III ratio. However, if too low a V/III ratio was used, the photoluminescence (PL) emission intensity was significantly reduced.

A 4 well strain compensated multiquantum well (MQW) structure has been grown on the (111)B substrate. Good intensity PL emission has been achieved at room temperature at about 1560nm. A blue shift in this emission is seen with increasing incident optical power. Similar structures grown on (001) substrates do not show this blue shift.

The X-ray rocking curves and PL data for these structures will be presented, together with initial photocurrent results.

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Dependence of electrical properties on the crystallographic orientation of CBr_4-doped GaAs epilayers grown on GaAs substrates by metalorganic chemical vapor deposition

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The non-planar patterned GaAs epilayers are useful in fabricating quantum structures. However, the impurity incorporation in these epilayers has different trend with varying the crystallographic orientations. Thus, to fabricate the novel structure, it is very important to know the mechanism of impurity incorporation according to the variation of the crystallographic orientation. In the previous work by Condo, et al, the several impurity incorporations were carried out with varying the crystallographic orientations [1]. An intentional carbon(C) incorporation has been widely studied because C has low diffusivity, low memory effect and possibility to acquire high doping levels [2,3]. For C incorporation, numerous sources have been used with a variety of growth techniques, such as a graphite filament, trimethylgallium(TMG), CCl_4, etc. However, the doping mechanism of C incorporation by using CBr_4 have not been well investigated, yet.

In this work, we have investigated the dependence of electrical properties on the crystallographic orientation of CBr_4-doped GaAs epilayers grown by atmospheric pressure metalorganic chemical vapor deposition (MOCVD). For the analysis of the dependence on the offset angle toward (111)A, GaAs substrates had different crystallographic orientations, (100), (511), (311), (211) and (111)A. The electrical properties of GaAs epilayers were analyzed at room temperature by Van der-pauw Hall measurement. The growth temperature was varied from 550 to 650°C and V/III ratio from 10 to 60. CBr_4 flow rate was kept at 0.023SCCM.

The hole concentration as a function of offset angle was shown in Fig. 1. The dependence of the electrical properties on crystallographic orientation was reproduced at the growth temperature range from 550 to 650°C. At the higher growth temperature region, the hole concentration of GaAs epilayers became under the detection limit ($<5\times10^{15}$ cm^{-3}) of room temperature Van der-pauw Hall measurement. The electrical properties of CBr_4-doped GaAs epilayers showed a strong dependence on the crystallographic orientation of the epilayer. At the given growth temperature range, the hole concentration drastically dropped at (511)A when compared with (100). From (511)A to (311)A the hole concentration increased, but it decreased again with increasing the offset angle to (111)A. This dependence of the hole concentration on the crystallographic orientation shows that the surface kinetics plays an important role in the C incorporation into the nonplanar GaAs epilayers, which would be related to the change of step density in the nonplanar surface of GaAs substrate [1]. With increasing growth temperature, the decrease in hole concentration would be due to the increase in the desorption rate of the adsorbed C-containing species at the growing surface and the increase of the decomposition of AsH_3 [4].

Fig. 2 shows the hole concentration as a function of offset angle with the V/III ratio varying from 10 to 60. With increasing V/III ratio, the hole concentration of GaAs epilayers decreased. The trend of the dependence of the electrical properties on crystallographic orientation was nearly same with the change of V/III ratio. The pathways of C reduction were reportedly enhanced by the increase in surface concentration of AsH_x species which increases the desorption rate of C-containing species from the growing surface, resulting in the decrease of the C incorporation in the epilayer.

In this study, it was concluded that CBr_4 was a controllable C source for p-type GaAs epilayers grown by atmospheric pressure MOCVD. The efficiency of C incorporation was strongly dependent on the crystallographic orientation.

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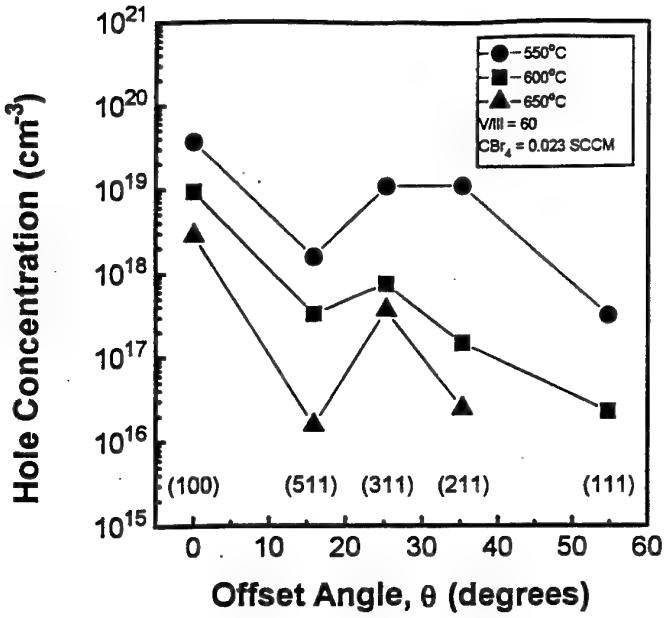

Fig. 1. Hole concentration of CBr_4-doped GaAs epilayers as a function of the offset angle toward (111)A at the growth temperature of 550, 600 and 650°C.

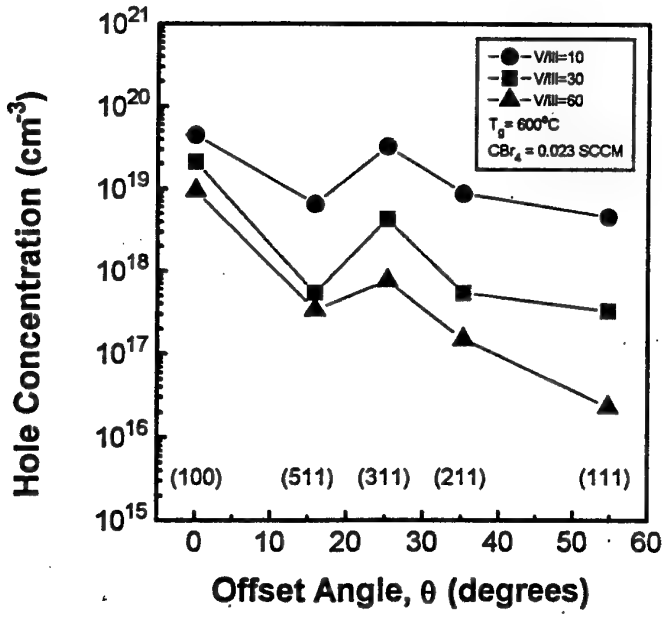

Fig. 2. Hole concentration of CBr_4-doped GaAs epilayers as a function of the offset angle toward (111)A at the V/III ratio of 10, 30 and 60.

Is the Be incorporation the same in (311)A and (100) AlGaAs?

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The use of p-type doping of (311)A GaAs/AlGaAs heterostructures has produced world-record two dimensional hole mobilities [Henini et al.,Applied Physics Letters 65, 2054 (1994)]. In that work, Silicon has been used as p-type dopant exploiting the preferential incorporation of Si on As site whenever the growth is performed on (N11)A oriented substrates, N¾3.

The purpose of the present study is two-fold: 1) to confirm that such advantages are still reachable with Be doping of (311)A AlGaAs and 2) to compare the incorporation of Be in (100) and (311)A AlGaAs (Al content of ‰0.24). The (311)A and the (100) samples, grown side-by-side by MBE with different doping concentration (NA up to 10^{18} cm^{-3}), have been characterized by low temperature photoluminescence and by electrical measurements. Then modulation doped samples have been grown on these two orientations.

Due to the different NA, it was possible to identify the Be related luminescence features. Values for the Be binding energies independent of the sample orientation but slightly lower than the commonly accepted ones [L. Pavesi and M. Guzzi, J. Appl. Phys. 75, 4779 (1994)] emerge from this analysis. However, different spectral broadening of the luminescence features are observed: thinner for the (311)A than for the (100) samples. Considering that the width of the free electron to hole bound to Be acceptor (e-Be) luminescence band of the (311)A samples is among the thinnest one published in the litterature, we attribute the wider features measured for the (100) samples to a band tail induce broadening. Since the electrical data show a sligthly larger compensation in the (100) than in the (311)A samples, these band tails are probably ascribable to ionized impurity tailing and not to alloy fluctuations . A significant two-dimensional hole gas mobility improvement is observed in the (311)A modulation doped AlGaAs/GaAs heterostructure sample with respect to the similar (100) sample. The Be doped (311)A hole gas has equal properties to the Si doped (311)A hole gas which should indicate that the superior properties of the (311)A sample are due to better interfaces and a reduced residual impurity incorporation.

Optical study of ZnSe grown on GaAs (110) surface

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Growth of II-VI materials on cleavage-induced GaAs (110) surface is attracting much attention recently because of the possible realization of low-dimensional structures of these materials.[1,2] In this paper, we report the optical spectroscopy of ZnSe grown on GaAs (001), (110) substrates and cleavage-induced(C-I) GaAs (110) surfaces. ZnSe grown on C-I (110) surface shows better quality than on other surfaces. In addition, higher growth temperature yields better luminescence from ZnSe grown on C-I GaAs (110).

GaAs (001) and (110) substrates were mounted on to a Mo holder by In melt. Another piece of GaAs (001) was mounted in between them vertically to the holder. This piece of GaAs was for getting a clean GaAs (110) surface by cleavage. The holder was then moved into the MBE chamber and the cleavage was performed at a vacuum pressure of ~ 10^{-8} Torr. RHEED pattern shows that the C-I (110) surface was very smooth.[1] The holder was then heated up to remove the surface oxidation of GaAs (001) and (110) substrates. Indicated by RHEED observation, the surfaces of both (001) and (110) GaAs substrates were clean and flat after the thermal treatment. RHEED pattern of the C-I GaAs (110) surface was almost the same as that just after cleaving. The temperature of the holder, monitored from the back side of the holder, was then lowered to the growth temperature. The MBE growth was done using solid sources. The beam flux of Zn and Se was 4×10^{-7} and 1.2×10^{-6} Torr respectively. The film was considered to be fully strain-relaxed because the thickness was much exceeded the critical thickness. The photoluminescence (PL) spectra were recorded at 2K using Spex 0.5-m monochromator. A 325-nm He-Cd laser was used to excite the luminescence. The reflectance spectra were taken using tungsten lamp.

The PL and reflectance spectra of the ZnSe grown at 410 °C were shown in Fig. 1. The prominent emission lines were from the free exciton (Ex), donor-bound exciton (I_2) and dislocation related emission (Y). The position of Ex emission line (4425.5 Å, 2.802 eV) was in good agreement with the sharp variation observed in reflectance spectra, indicating that this emission was originated from the free exciton. The Y line at 4762 Å (2.603 eV) was attributed to extended defects such as dislocations. The intensity ratio, Ex/Y, is believed to reflect the crystal quality of the films. This ratio was found to be 1.6, 1.3, and 1.0 for growth on C-I (110), (110) and (001) substrates, respectively, indicating the higher quality of the film grown on C-I (110) surface. The better quality associated with the C-I (110) surface is believed to be related with the clean and smooth surface obtained by cleaving. This result reveals the initial surface affects significantly the quality of the film.

It was further found that the Ex/Y ratio changes with growth temperature remarkably. Figure 2 presented the PL spectra of ZnSe films grown on C-I (110) surface at different temperatures. For each growth temperature, we observed strong emission lines of Ex, I_2 and Y. However, at the higher growth temperature of 410 °C, not only the absolute emission intensity from free exciton increased, but also the 2s excitonic emission became stronger. The Ex/Y ratio was 1.6, 0.7, 0.4 for growth temperatures of 410, 320, 290 °C, respectively. These observations indicate that better quality can be obtained on C-I GaAs (110) by a higher growth temperature.

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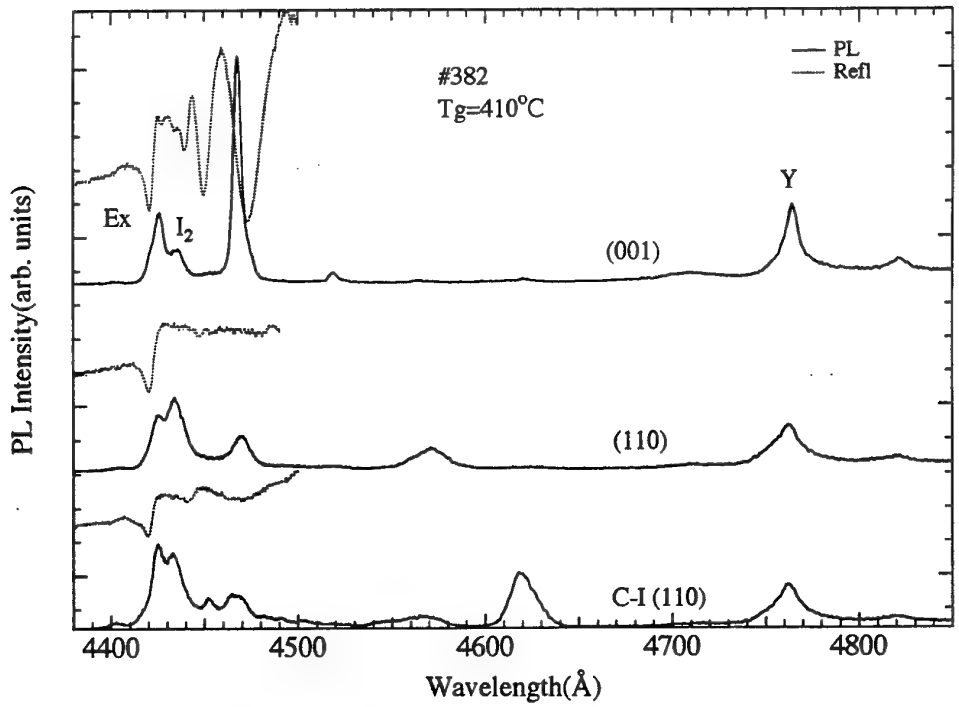

Fig. 1 PL and reflectance spectra of ZnSe grown at 410 °C on GaAs (001), (110) substrates and C-I GaAs (110) surface.

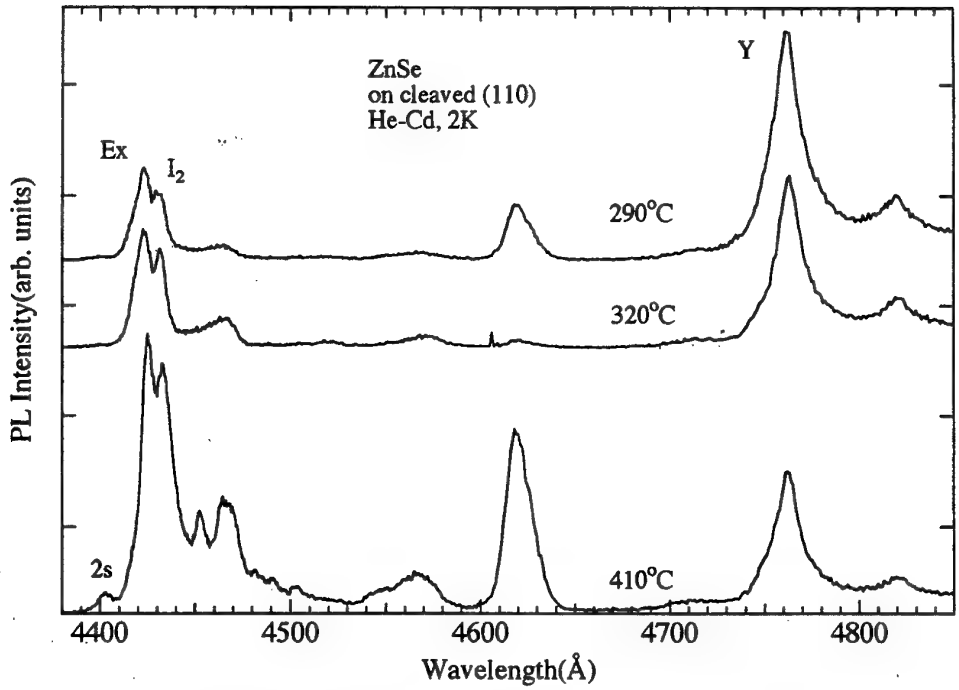

Fig. 2 PL spectra of ZnSe grown at different temperatures on C-I GaAs(110) surface.

Structural characterization of InGaAs/InAlAs quantum wells grown on (111)-InP substrates

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The possibility of changing and improving the fundamental material properties, growth mechanisms, surface kinetics and impurity incorporation by growing on crystal orientations other than (100) has motivated a strong effort to study these aspects. In particular, recent studies about HEMT structures according to their growth orientation have attracted much interest from the viewpoint of physics and novel device applications. It has been reported that (111)-oriented quantum wells exhibit considerably better properties compared to those grown along the (100) direction. However, the optimization of these properties needs a high degree of crystalline quality. In this work, the structural properties of the layers present on InGaAs/InAlAs HEMT structures grown on (111)-InP substrates have been analyzed by Atomic Force (AFM) and Transmission Electron (TEM) microscopies.

Two series of samples have been studied, with (A) and without (B) quantum well. AFM results show that the surface morphology is quite different. Whereas samples A are characterized by the presence of a large density of triangular platforms surrounded by trenchs of $\sim$30nm depth, samples B show pits with average length of $\sim 1\mu$m and depth bigger than 50nm.

In order to analyze the origin of these defects, TEM observations have also been carried out. In samples A, planar view observations show three main types of defects distributed irregularly over the surface: near-closed triangles formed by accummulations of defects which can be related to the trenchs observed by AFM, threading dislocations scrambled in tangles and few defective zones where only the usual fine contrast modulation can be seen. In contrast, in samples B there are stacking faults and isolated threading dislocations much more uniform all over the surface. Cross-sectional images indicate that the nucleation sites are different in both cases: defects in samples A start above the strained quantum well while in samples B they nucleate immediately above the buffer/substrate (InAlAs/InP) interface. The results show that an accurate control of the growth conditions is necessary to obtain acceptable structural quality for (111) devices.

Structural comparison of arrays of InAs quantum boxes grown respectively on a GaAs substrate and on a GaAs-on-Si substrate

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Heterostructures including an array of InAs/GaAs quantum boxes obtained by 3D growth mode and a single high quality InGaAs quantum well have been grown by MBE [1]. Two samples have been grown in the same conditions on an GaAs substrate and on a commercial GaAs-on-Si substrate respectively (for the latter, the dislocation density is estimated at 10^7 per cm^2). The overall structure has been grown at 520°C. An amount of 2 monolayers of InAs has been deposited within 20 seconds to obtain the InAs islands.

The photoluminescence spectras revealed a drastic reduction of the emission from the InGaAs quantum well when using the GaAs-on-Si substrate with regard to the GaAs substrate. On the contrary, the emission of the InAs quantum boxes is similar in both samples, with however a shift towards higher energy when using the GaAs-on-Si substrate.

The dot size and density were determined by Transmission Electron Microscopy in both samples. The islands obtained on the GaAs-on-Si substrate have been found to be smaller than on the GaAs substrate. This attributed to the residual strain in the GaAs-on-Si substrate, which increased the actual lattice mismatch.We also observed how the threading dislocations coming from the GaAs-on-Si substrate behave when they cross the InAs/GaAs quantum boxes array.

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OPTICAL CHARACTERIZATION OF HIGH MISMATCHED InP/GaAs(111) EPITAXIAL LAYERS

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Abstract:

In recent years, tremendous developments have occurred in the field of III-V material heterostructures because of their flexibility for tailoring the electronic and optical properties for specific applications.

In particular, there has been an increasing interest in the medium mismatched InP/GaAs epitaxial layers due to their potential for integration of high speed GaAs electronics with InP based opto-electronic devices.

In this work, we investigate heteroepitaxial layers of InP with different thicknesses grown by metalorganic chemical vapor deposition on (111) surfaces of GaAs subtrates.

The growth on (111) oriented substrates is of interest since the critical thickness predicted by the mechanical equilibrium theory is about twice that for growth on (100) oriented substrates, and when we reach this critical thickness, the density of dislocations is lower.

The heteroepitaxial layers are investigated by low temperature photoluminescence (PL) and photoluminescence excitation (PLE). We use the PLE for the determination of the residual stress witch is caused by the different lattice parameters of layers and substrate. The optical results will be compared with DDX measurements.

The Growth of InGaAs quantum well on GaAs(111)A, (211)A and (311)A substrates

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The ability to grow high quality (InGa)As on non (001) surfaces will be vital for the development of a wide range of novel optoelectronic devices, however it has, as yet, received little attention. In particular In containing heterostructures grown on GaAs {111} have the advantage of large inherent piezoelectric coefficient and a critical thickness calculated to be significantly larger than that for similar structures grown on GaAs(001). There has been some study of structures grown on the (111)B orientation , but use of the A surface offers further distinct advantages.

Si is an amphoteric dopant in molecular beam epitaxy, MBE, growth of GaAs (111)A and its incorporation behavior can be easily controlled by the growth conditions. This eliminates the need to use the traditional p-type dopant, Be, which tends to be less pure and has a very large diffusion coefficient.

Previous work has shown that the growth of In containing structures on GaAs(111)A is problematic, reflected in the very broad, weak and strongly red shifted peaks observed in photoluminesence (PL) spectra from GaAs:In 0.2Ga 0.8As quantum well, QW, structures . The origin of this broadening is unclear but probably relates to the difficulty in choosing appropriate conditions for the growth III-V's on the (111)A surface. We have undertaken a comprehensive study of the growth of 80Å, 15% InGaAs single QWs on the GaAs(111)A, (211)A and (311)A surfaces. The quality of wells grown on the (211)A and (311)A are rather insensitive to growth conditions in contrast to those on the (111)A where good quality wells can only be obtained bygrowth at low substrate temperature under a high V:III ratio. A (111)A 80Å, 15%InGaAs single QW with a 12K PL peak width of less than 8meV was be obtained by growth of the well at 400°C under a V:III ratio of 5:1. This is by far the narrowest ever reported for this system.

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STRAIN INDUCED PIEZOELECTRIC FIELD IN $In_xGa_{(1-x)}As$ / $In_{0.52}Al_{0.48}As$ QUANTUM WELLS GROWN ON (111)B InP SUBSTRATE.

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ABSTRACT

We have investigated the excitonic transitions in (100) and (111)B oriented In(x)Ga(1-x)As/In(0.52)Al(0.48)As quantum wells grown on InP substrate. Using a self-consistent Schrödinger-Poisson model, we have theoretically demonstrated the quantum and strain induced effects on the e1-h1 transition energy in the (111)B oriented quantum wells. The strain induced piezoelectric field has been considered and the Quantum Confined Stark Effect included in the calculations. We present the experimental room temperature phototransmittance spectra of (100) and (111)B oriented, compressively strained, $In_xGa_{(1-x)}As$ / $In_{0.52}Al_{0.48}As$ As single quantum wells grown by Molecular Beam Epitaxy on InP substrate. The calculation model has been applied in order to identify the excitonic features observed on the spectra. The experimental piezoelectric field in the (111)B oriented single quantum wells has been calculated to be equal to 190 kV/cm, slightly superior to the 175 kV/cm expected from the theory.

PIEZOELECTRIC CONSTANT DETERMINATION FROM PHOTOREFLECTANCE MEASUREMENTS IN STRAINED InGaAs/AlGaAs LAYERS GROWN ON POLAR SUBSTRATES ,

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ABSTRACT

Photoreflectance measurements of internal piezoelectric fields are performed on UN+ structures which consist of a strained InGaAs quantum well embedded in AlGaAs undoped barrier layers, grown on polar substrate orientation (<111B>). Using such a direct electric field determination, no theoretical modelling is necessary to get a quantitative value of the piezoelectric field as a function of In composition. No assumption regarding the quantum well shape nor the indium segregation effect is needed. A good precision is obtained provided that the barrier material composition is accurately known.

Our experimental results give piezoelectric field values which are twice lower than the theoretical expression calculated with linearly extrapolated values of elastic constants C_{ij} and piezoelectric constant e_{14}, between the two extreme binaries GaAs and InAs. As the elastic constants C_{ij} are generally known with a good accuracy, we assume that the actual value of e_{14} may be twice lower than the values usually referred to in the literature, which is only based on a single experimental determination. This assumption is in good agreement with previous results that we obtained in other structures, as well as with other experimental determinations.

MBE Growth of AlGaAs/GaAs Double-Heterostructure LEDs on GaAs(111)A and (211)A Substrates Using All-Silicon Doping

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Silicon is widely used as the n-type dopant in GaAs growth using molecular beam epitaxy (MBE). However, it has been reported, that in GaAs growth on GaAs(n11)A substrates, Si atoms are incorporated as acceptors when $n \leq 3$[1]. We have previously reported that the Si-doping type can be controlled by growth conditions in the GaAs growth on GaAs(n11)A[2] and demonstrated a GaAs p-n junction LED grown on GaAs(111)A using only Si dopant[3]. We have also reported MBE growth of AlGaAs p-n structure on GaAs(111)A substrates using only Si dopant[4]. These techniques are attractive because AlGaAs/GaAs p-n structures can be grown using only Si dopant.

In this paper, we report on MBE growth of AlGaAs/GaAs double heterostructure (DH) LEDs grown on GaAs(111)A and (211)A substrates using only Si dopant. After chemical etching, the substrates were heated to 700°C. Then, a 1-μm thick n-type $Al_{0.3}Ga_{0.7}As$ layer was grown at 540°C with a V/III flux ratio of 7. After changing the V/III flux ratio from 7 to 2, a 0.08-μm thick non-doped GaAs layer and a 1-μm thick p-type $Al_{0.3}Ga_{0.7}As$ layer were grown. Only Si was used as a dopant, and the Si cell temperature was varied to maintain the carrier concentration at 1×10^{18} cm^{-3} for both the n-type and p-type AlGaAs layers.

Cathodoluminescence spectra and I-V characteristics of the samples confirmed that the p-i-n structure was obtained. The peak wavelength of the emission spectra for both the (111)A and (211)A samples was 875 nm at 300K, and this peak is attributed to the emission in the i-GaAs layer. The peak intensity of the (211)A sample is stronger than that of the (111)A sample. This is caused by the smooth AlGaAs/GaAs interface structure on (211)A. Silicon p-type dopant has a higher temperature stability than Be. Our results indicate that a p-n structure grown using only Si dopant improves device quality.

This study shows that MBE growth on GaAs(111)A and (211)A substrates using only Si dopant is a promising technique for fabricating a new kind of AlGaAs/GaAs DH laser diode.

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Lateral Tunneling Transistors Fabricated by Plane-dependent Si-doping in Nonplanar Epitaxy on GaAs (311)A and (411)A Substrates

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Tunneling transistors with negative differential resistance (NDR) characteristics have attracted much interest because of their great potential in multifunctional device applications due to their unique current-voltage characteristics. However, there are still some problems in the device fabrication process; e.g., a complicated process is required to fabricate the gate electrode onto vertical tunneling junctions[1] or a regrowth process is required to obtain a lateral tunneling junction.[2] To realize tunneling transistors without this complicated fabrication process, we used a plane-dependent Si-doping technique in nonplanar epitaxy. Since Si atoms are incorporated as acceptors in GaAs growth on (N11)A (N<4) substrates,[3] a lateral p^+-n^+ interband tunneling junction is formed by growing a heavily Si-doped layer on a patterned (N11)A substrate. Recently, we reported on a lateral tunneling junction with NDR characteristics due to interband tunneling fabricated on patterned (111)A substrate and demonstrated a lateral tunneling transistor at 77 K.[4] In this paper, we report on the NDR characteristics of lateral tunneling junctions formed on patterned (311)A and (411)A substrates and the room temperature (RT) operation by optimizing the structure of a lateral tunneling transistor.

Figures 1(a) and 1(b) show schematic cross-sectional views of fabricated lateral tunneling devices on patterned GaAs (311)A and (411)A substrates. Extra (411)A and (311)A facets were formed on the top corner of the sidewall during MBE growth on patterned (311)A and (411)A substrates, respectively. The interband tunneling junction was formed between the top surface and the facet. It is noticeable that the conductivity type of the top surface of lateral tunneling junctions are opposite for patterned (311)A and (411)A substrates. This result indicates that both "p-based" and "n-based" lateral tunneling transistors can be fabricated by choosing the proper substrate orientation; for example, "n-based" means that a drain current increases as a gate voltage increases. The peak current (Ip) density was strongly affected by the buffer layer thickness as shown in Fig. 2. The Ip density increases as the buffer layer thickness is increased; the Ip density of 202 A/cm^2 is obtained when the buffer layer thickness is 1.2 μm. In this case, the peak-to-valley ratio (PVR) was 5.4.

A MIS-structure was used as the gate electrode to reduce the gate leakage current, and it was placed on the (411)A surface close to the tunneling junction as shown in Fig. 1(b). Figure 3 shows the drain current-voltage characteristics of the "n-based" lateral tunneling transistor at RT. The drain voltage was swept from 0.0 to 0.5 V with the gate voltage applied in steps of 3.0 V from -1.5 to 4.5 V. Gate-controlled NDR characteristics were clearly observed even at RT. The peak drain current density was modulated from 161 to 251 mA/cm^2, and the PVR was modulated from 3.1 to 4.4. These results indicate that the tunneling current is modulated through both carrier concentration and tunneling barrier width modulation by changing the gate voltage.

We have demonstrated the room temperature operation of a lateral tunneling transistor fabricated by the plane-dependent Si-doping technique in nonplanar epitaxy. This technique provides a simpler process for the fabrication of tunneling transistors.

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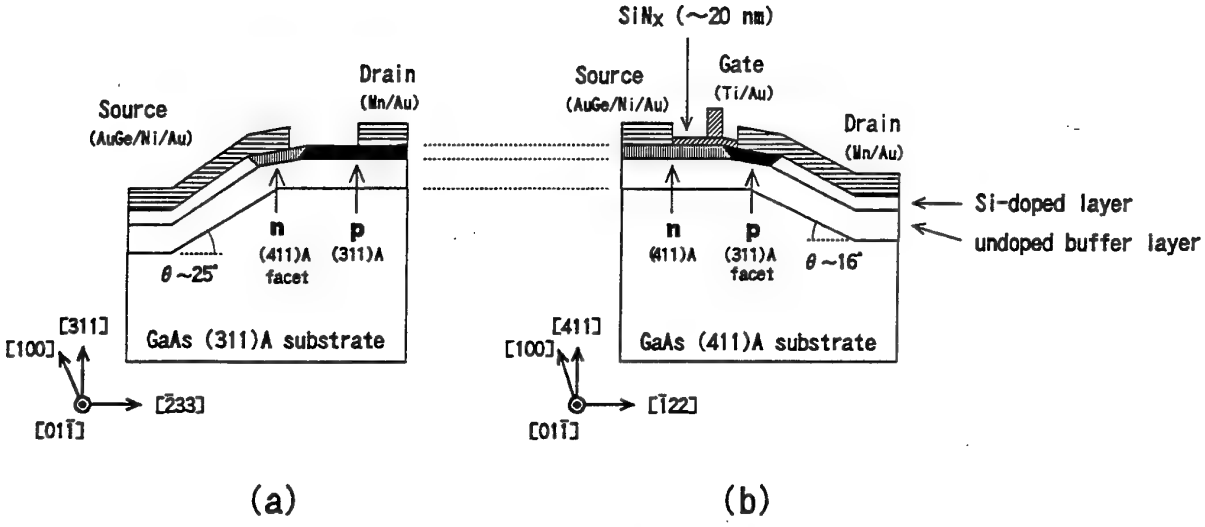

Fig 1. Schematic cross-sectional view of the lateral tunneling device. (a) A lateral tunneling diode fabricated on (311)A patterned substrate. (b) A lateral tunneling transistor fabricated on (411)A patterned substrate. Gate length is 4 μm.

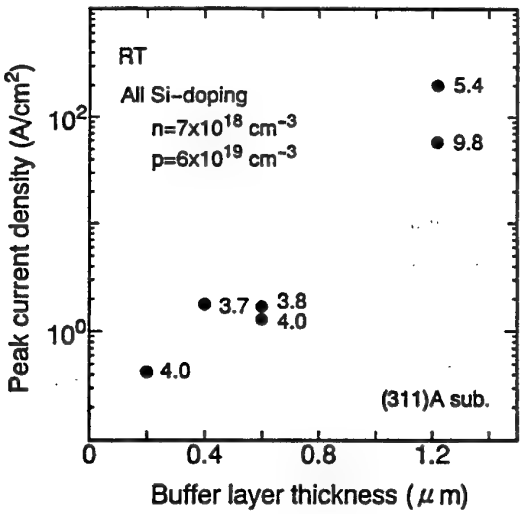

Fig 2. Peak current density dependence on buffer layer thickness in lateral tunneling diodes fabricated on (311)A patterned substrates. PVRs are also indicated on the right-hand side of each circle.

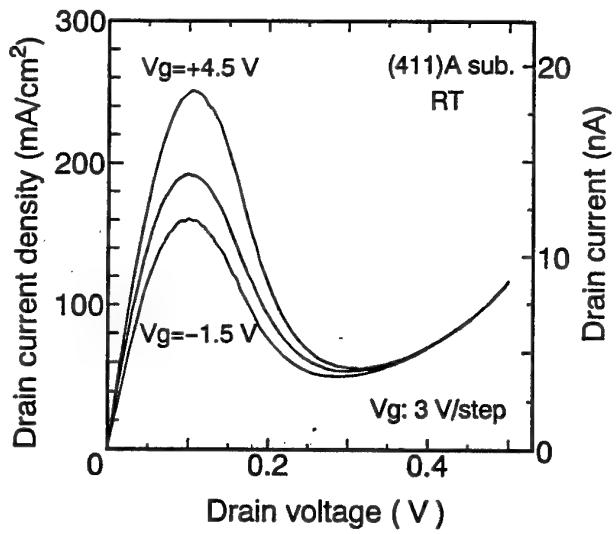

Fig 3. Room temperature drain current-voltage characteristics of the lateral tunneling transistor fabricated on (411)A patterned substrate. Drain voltage was swept from 0.0 to 0.5 V with the gate voltage applied in steps of 3.0 V from -1.5 to 4.5 V. Gate-controlled NDR characteristics were clearly observed.

Role of surface energy of (001) and (11n) facets on the 2D to 3D growth mode transition of strained $In_x Ga_{1-x}As$ layers on InP(001)

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It is now well established that highly mismatched (>2%) heteroepitaxy can evolve from a 2-dimensional (2D) to a 3-dimensional (3D) growth mode before the occurence of plastic relaxation. Previous experiments and models revealed that the main parameters controlling the 2D-3D growth mode transition are elastic strain, surface energy and surface diffusion kinetic.The present work aims to show that surface energy can be in some cases, the predominent parameter controlling the surface morphology of strained layers and consequently the growth mode. This was evidenced by comparing the 2D-3D critical thicknesses and the surface morphologies for 2% mismatched $In_xGa_{1-x}As$ films grown on InP(001) by Molecular Beam Epitaxy (MBE) in different situations : i) either in compression, x=0.82 or in tension, x=0.25, ii) either non-intentionally-doped (nid) or highly-doped and iii) surfaces either As-stabilized or cation-stabilized during growth. Experiments were done using Reflexion High Energy Electron Diffraction (RHEED) and ultra-high vacuum Scanning Tunneling Microscopy (STM).

We have shown that when minimizing kinetic effects by using near equilibrium growth conditions, the surface energy through surface reconstructions can be a preponderant parameter. Because the As terminated (001) surface may be strongly stabilized if reconstructed by surface dimers, any effect which modifies the long range ordering of this reconstruction (as doping may do) or its efficiency (as tension may do) will advance the 2D-3D growth mode transition onset, all thing being equal in the final state. In tension, the breaking of the surface reconstruction leads to a roughening of the surface which partially relaxes the strain energy and thus delays the strong 2D-3D growth mode transition. On the other hand, changing growth conditions, from As stabilisation to cation stabilisation prevents a 3D growth mode because facetting of the (001) plane into (11n) faces is energetically unfavourable because of the high surface energy of cation-stabilized (11n) faces.

Piezoelectric effect in micromachined [001] quantum wells : theoretical aspects.

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In this work, we propose to take advantage of piezoelectric effect in systems primarily grown on [001] GaAs substrates. Such an effect can be achieved by making use of elastic relaxation of micromachined strained quantum well structures, the etching direction being carefully chosen.

Micromachining of strained quantum well structures has already been successfully used for providing large lateral band gap energy modulation, suitable for lateral optical mode confinement and lateral quantum confinement of excitons [1]. Total or partial elastic relaxation of strained layers was obtained by selective etching (along [010] direction) which releases and makes free-standing the quantum well structure.

For this study we have chosen to consider a selective etching along [1-10] direction, producing wide cantilevers. In this case the released cantilever is somewhat uniaxially strained along its anchorage direction. We have thus calculated the strain state of the quantum well structure far enough from its anchorage line, by applying the general modelisation given in [2]. Once the strain tensor components of each material were known, we have calculated the transitions energies on the basis of 8-band k.p description proposed by Bahder [3] and developped by Gershoni et al. [4] for laser applications.

The resulting piezoelectric field in a 200 Å wide Ga0.8In0.2As quantum well sandwiched between two 100 Å wide Ga0.7Al0.3As barriers appears to be high enough (80 kV/cm) for piezoelectric effect to be important : more than 70% of the transition energy shift (compared to the unreleased strained well) is due to the piezo electric field.

A comparison with transitions in a similar system, but with etching direction along [100] axis demonstrates a higher shift for the piezoelectric system. The corresponding experiments are currently in progress.

This effect appears to be very promising for tailoring properties in monolithic integration of semiconductor optical devices.

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Comparison Theory-Experiment in T-shaped Quantum Well Wires

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T-shaped quantum well wires are built with two quantum wells whose growth axes are respectively [001] and [110], the wire being parallel to [1-10]. Recently experiments have been performed on such wires[1,2]. In Ref.1 and 2 the exciton binding energy is experimentally determined. The purpose of the paper is to show how it is possible to compare theory and experiment taking into account the exact symmetry of the Γ_8 valence band. We recover the experimental results but we show the interpretation of the experiments can be strongly modified. In particular the blue shift does not result from the increase of the exciton Rydberg in all cases but can result from the decrease of the electron confinement energy.

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COMPUTER SIMULATION OF THE GROWTH OF HETEROSTRUCTURE SYSTEMS

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The growth of low dimensional heteroepitaxial systems has been a subject of intense experimental and theoretical study for the last several years, driven by the technological importance of heterostructures. Of particular interest is the fabrication of quantum wires (QWR) by facetted MBE regrowth.

We have investigated the growth of heterostructures on the patterned substrates leading to the formation of semiconductor QWRs using Monte Carlo simulation technique. Our simulation model includes real tetrahedral lattice structure of semiconductor materials, atom-atom interactions out to second nearest neighbors, and surface reconstruction effects. The strain effects which inevitably take place during the growth of QWR or quantum dots have been also included in our model.

The formation of semiconductor quantum wires on the top of ridges and by deposition through shadowing mask has been obtained in our simulations. The growth of QWR with the top (001) surface and (111) sidewalls has been shown. The formation of (111) sidewalls with higher quality than that of top (001) surface has been obtained due to higher mobility of atoms on (111) surface. The dependence of the quality of quantum wires on the substrate temperature has been shown.

Simulation of the deposition of lattice mismatched materials on non patterned surfaces have also been performed. Due to strain effects in deposited layers, surfaces are shown to become rough at early stages of the growth. The morphology of the surface shows grooves and elongated islands presenting (111) facets. However, the aspect ratio of these islands do not seem to be ideal for the formation of QWRs. Size distribution of islands has been studied as a function of growth parameters. It is shown that the size distribution is correlated with the variations of strain energy inside these islands.

In conclusion, the higher quality of QWRs grown on patterned substrates or through masks has ben demonstrated.

DEFECTS DENSITY INFLUENCE ON THE SI/SIO$_2$ INTERFACE ROUGHNESS BY ATOMIC SCALE SIMULATION

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It is well known that the Si/SiO$_2$ based chip electronic properties lie mainly on a region about 30Å thick between the Si substrate and the grown oxide. The lake of performant models for ultrathin SiO$_2$ layers growth mechanism induces nowadays great efforts for a fundamental understanding of the silicon oxidation first ages.

Since the carbon atoms, as impurities, are frequent in the silicon substrate, we analyse in this paper their density influence on the Si/SiO$_2$ interface roughness, for concentrattion ranging from one carbon atom in a silicon unit lattice to four carbon atoms in a silicon unit lattice. We generate these impurities in the substrate upper layers to make more obvious their interaction with the oxygen atoms.
The substrate crystalline orientation is choosen to be (001) and (110) and the processing temperature is fixed at the value of 1200 K ($\approx$ 900°C). We deposit an ultrathin silicon diocide layer on the silicon substrate and by means of many body potentials limited to the two first terms, and the Metropolis test, we make relax the structure. At the equilibrium state, the structure final energy is minimized and the interface is already in its stable configuration.
For its characterization, we can use the position roughness or the potential energy roughness. The study of a surface roughness is done statiscally by the determination of the atoms which positions belong to a range of fixed magnitude h_0.
For the case of the interface roughness, we use here a different calculation procedure. For example, we define the position roughness as the standard deviation σ of each atomic position from its mean value μ.

$$\mu = \frac{\sum_i^N X_i}{N} \tag{1}$$

$$\sigma = \sqrt{\frac{\sum_i^N (X_i - \mu)^2}{N}} \tag{2}$$

X_i is the vertical position of the atom i, N the total number of atoms considered (at the interface). We will focus our investigation on the upper layer of the substrate for the interface morphology study.

We observe a great sensitiveness of the interface roughness on the C defects density. The defects inflence on the oxide is also found to be linked on the substrate crystalline orientation. The powerfull of our simulator is its possibility to give informations at atomic scale of the interface roughness without any physical damage on the atoms distribution. It helps to for good models buiding in the case of ultrathin films processing mechanism.